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THE MEASUREMENT OF HYDROSTATIC PRESSURE TO 30,000 kg/cm²

By P. W. Bridgman

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THE MEASUREMENT OF HYDROSTATIC PRESSURE TO 30,000 kg/cm^2

By P. W. Bridgman

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Introduction

A part of the problem of the extension of the controllable pressure range from 12,000 kg/cm^2 to 50,000 for certain phenomena and to 30,000 for others, a problem on which I have been engaged for the past few years, is to provide some method for the accurate measurement of pressure in the new range. For such phenomena as polymorphic transitions high accuracy in the measurement of pressure is not of extreme importance, but for those phenomena whose chief interest lies in departures from linearity with pressure, such as compressibility or change of electrical resistance, a higher degree of precision in the measurement of pressure is obviously desirable.

In the range of my earlier work, mostly up to 12,000 kg/cm^2, pressure was usually measured in terms of the change of resistance of a coil of manganin wire.[1] Before the resistance changes could be accepted as a satisfactory pressure indicator a preliminary study was made of the change of resistance against an "absolute" gauge of the free piston type. The resistance change of any one coil of wire proved to be linear in the pressure within 0.1 per cent up to 13,000 kg/cm^2, but different coils cut from the same spool might differ in their constant of proportionality by 2 or 3 tenths of a per cent, and coils from different manufacturers might differ by several per cent. A calibration of each individual coil in terms of some easily reproducible standard which determines a pressure fixed point was therefore indicated. For this fixed point the freezing pressure of mercury at 0° C. has been used in all my work; this pressure was found by original measurement against the piston gauge to be 7640 kg/cm^2.

In work already published[2] up to 30,000, and also in some earlier work to 15,000 and 20,000, pressure has been measured with a manganin gauge, by linear extrapolation of the constant determined at 7640. There was various evidence that any error in such an extrapolation could not be large, but now that I have started on a measurement in this range of the compressibilities of the relatively incompressible metals the time has obviously come to make the measurement of pressure as precise as possible. One would naturally first try to merely extend the former procedure to higher pressures, but this is not feasible because the free piston gauge had about reached its limit at 13,000, due to rapidly increasing viscosity of the pressure transmitting medium, demanding forces to rotate the piston great enough to break it, and also due to the rapidly increasing distortion, the correction for which can only be calculated by the methods of the theory of elasticity in a range in which the fundamental assumptions of the theory are becoming rapidly inapplicable. However, the fundamental idea of the free piston gauge, namely the measurement of pressure by measurement of the thrust on a piston in equilibrium with the pressure, appears to remain the simplest and perhaps the only method. The errors to which this is subject are two: those arising from friction and those arising from geometrical distortion. If these two sources of error could be overcome, then an extension of the same procedure as before could be used, namely direct measurement of some easily determined pressure fixed point against which the manganin gauge could then be calibrated and used thereafter as a secondary gauge. This is the course adopted in the following. By suitable design of the apparatus the friction has been cut down to a low figure; the corrections due to distortion have been determined by direct measurements of the interior bore of the apparatus while under pressure; the pressure of a suitable transition between solid phases has been determined as a pressure fixed point; and the manganin gauge has been calibrated in terms of these, and its departure from linearity determined. A variant of the former arrangement is that now the piston on which the thrust is measured is in direct contact with the solid undergoing transition, with no liquid as intermediary; in this way the problem of leak past the piston is minimized.

INSTRUMENTAL DETAILS

The chief frictional resistance to the motion of a piston arises at the periphery of the piston, in the packing; other things being equal it is proportional to the ratio of the active area of the packing material to the area of the piston. This ratio can obviously be cut down by making the ratio of periphery to piston area small, and by making the packing as thin as possible. There is then an advantage in working on a large scale, because the larger the scale the smaller the ratio of periphery to piston area. The diameter of the free piston formerly used to 13,000 was only 0.0625 inch; for this work up to 30,000, 0.5 inch was used. In fact, the cylinder containing the material undergoing transition, the piston, and the presses for pushing the piston, were the same as previously used in measuring the effect of pressure on resistance up to 30,000, and have already been sufficiently described.[2] The ½ inch piston producing the high pressure is pushed by a 3.5 inch piston, thus giving a multiplication of 49. The 3.5 piston is actuated by a hand pump connected to a calibrated 0.25 inch free piston gauge, similar to that used in much of my previous work. The pressure on the 3.5 piston does not rise above 10,000 lb/in^2, so that the weights on the 0.25 free piston gauge do not get above 500 pounds, which is easily manageable. Friction occurs both on the 3.5, and mostly on the 0.5 inch piston. Friction on the 3.5 inch piston is cut down by making the bore of the cylinder of the press as smooth as possible, and by using for packing material a disc of "Duprene" only 1/16 inch thick, instead of the ¼ inch thickness usually employed. The Duprene is held between brass discs ⅛ inch thick, which are a smooth sliding fit for the hole. The life of the packing is naturally cut down by using only 1/16 inch thickness, but it nevertheless is long enough to permit measurements with no inconvenience on this score. With these dimensions, the ratio of packing area to area of the piston is only 0.07.

The 0.5 high pressure piston was of carboloy, as in all this work. I am very much indebted for it to the Carboloy Company. This piston was made 0.010 inch smaller than the hole, so that there is no friction at the carboloy, but only at the end, where it pushes a packing disc against the solid undergoing transition. The construction of this packing disc is indicated in Figure 1. It consists of a disc of hardened steel, an easy push fit for the hole, and only 0.020 inch long on the straight part, bevelled below to an angle of 45° and pushing a conical packing ring of either beryllium-copper or phosphor-bronze, itself 0.035 inch thick. The endeavor is to make the thickness of the packing ring as small as is compatible with its not blowing out past the hardened steel disc.

Another most important factor in determining friction is the length of the slug of material undergoing transition. Before the transition occurs there is of course appreciable volume compression of this material, which demands that the material slide in an axial direction along the walls of the container. This sliding is accompanied by friction, which resists the propagation of pressure, so that the pressure in the lower end of the slug is less than that in the upper end immediately under the moving piston. The material immediately under the piston may therefore be undergoing transition while that at the lower end is still below the transition pressure. There is the converse situation when the transition is approached from the other side, with release of pressure. The difference of pressure between the top and bottom increases exponentially with the length of the slug. Furthermore, after every change of pressure the

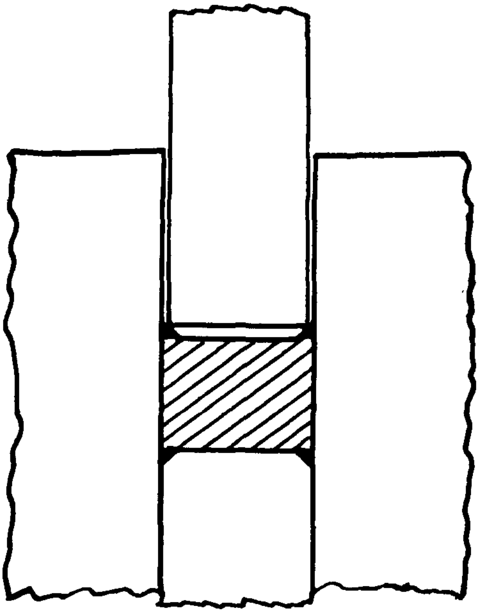

FIGURE 1. Method of packing the substance undergoing transition so as to give minimum friction.

volume does not immediately take up its final value, but there is a frictional creep, which simulates the transition, and which rapidly becomes more important the longer the slug. Because of these two effects a large amount of material, that is, a long slug, is disadvantageous, but on the other hand, the greater the amount of material, the greater the volume change during the transition, and therefore the greater the ease of following the course of the transition and making measurements. The solution is to be found in decreasing the amount of material and at the same time increasing the sensitiveness of the method of measuring piston displacement, and also, of course, in using a transition with as large a volume change as possible. In this work the volume change of the material used, bismuth, is about 5 per cent, the length of the slug was only 0.375 inch with a diameter of 0.5 inch, and the piston displacements were read with a 0.0001 inch Ames dial gauge, which is sensitive to 0.00001 inch by estimation of tenths of the smallest divisions. Even with this favorable combination, frictional creep after every change of pressure is perceptible; one cannot be sure that the transition is running unless the creep exceeds something of the order of 0.0001 inch per minute.

Corrections for Distortion

The containers used in determining the fixed points were the regular "cylinders" used in previous work to 30,000. It will be remembered that these are somewhat tapering on the outside, and that simultaneously with the development of internal pressure they are pushed into a tapered collar fitting the outside, thus producing an external pressure which rises simultaneously with the internal pressure. The cylinder thus remains entirely within the elastic range and shows neither creep nor permanent alteration of dimensions after exposure to pressure. It is formally possible to calculate the change of cross section, but the calculations could be only approximate even if the equations could be solved exactly, because the boundary conditions are not well defined. Furthermore, the stresses are so high that deviations from the linearity assumed in elasticity theory may be suspected to be perceptible, so that some experimental check, even if rough, on the calculations is desirable.

There seems to be no easy method of measuring the change of internal dimensions of the container while the transition is running, but it is possible to determine, as a function of pressure, the change of internal diameter of a similar container filled with a liquid, as in the previous measurements of change of resistance under pressure, instead of a solid. This was accomplished by a modification of the sliding wire method of measuring small changes of length already extensively used in measuring compressibilities. A forked spring, shown in Figure 2, pressing against the walls of the container, carries across its end a transverse high resistance wire, fixed to one tine of the fork and sliding over a contact fixed to the other. Measurement with a potentiometer of the potential difference between fixed and sliding contact when a known current flows through the wire affords the method of determining small changes of dimensions. A number of small corrections are involved in reducing the measured potential differences to displacement; these had been previously determined.

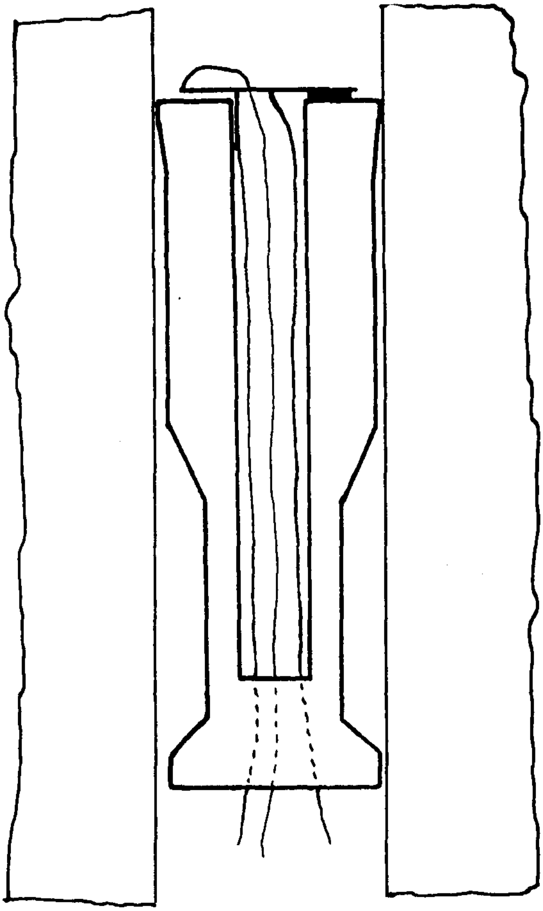

Figure 2. The sliding contact arrangement for measuring the change of internal diameter while under pressure.

A number of different set-ups were made with the apparatus for measuring distortion; most of the runs were incomplete because of one accident or another, but finally enough partial readings were obtained to give a satisfactory characterization of the behavior over the entire range. It is to be expected that the distortion of the bore of the cylinder will not be uniform along its length, being a maximum at the center of the stressed region, and a minimum at the ends, including the moving piston, where support is afforded by the parts of the cylinder walls not exposed to internal pressure. An attempt was made to find the distortion immediately under the moving plug by mounting the fork so that the cross wire is almost in contact with the lower end of the moving plug. In this arrangement the fork slides along the cylinder axis, pushed by the piston as it advances to increase the pressure. On release of pressure the fork is left standing in its extreme position. Measurements with increasing pressure therefore give the distortion at the moving plug, and measurements with decreasing pressure approximately the distortion at the center. Or the distortion at the center can be obtained both with increasing and decreasing pressure by placing the fork initially at the center.

The distortion determined in this way was in every case linear with pressure within limits of error. The distortion at the moving plug turned out to be 2/3 of that at the center. It may be shown theoretically, by an application of Betti's reciprocal theorem, that the distortion at the *packing* of the moving plug should be only one half the distortion at the center, where it is a maximum, assuming conditions for a semi-infinitely long thick cylinder. That is, if it had been possible to measure the distortion at the packing instead of some distance away at the end of the plug, theory would demand a value ½ that at the center instead of 2/3 as found. It would seem that the discrepancy is sufficiently accounted for by the difference of location, and in the following the factor ½ was therefore used in calculating the correction at the packing, which determines the effective cross section of the piston. The correction so found is a 0.57 per cent increase in area at 25,000 kg/cm^2. The correction thus found has to be still further modified for the finite length of the slug undergoing transition, the correction determined under the experimental conditions above being for a semi-infinitely long cylinder. It would probably be difficult to calculate this correction exactly, but a rough graphical estimate may be made of it. The radial distortion of an infinitely long cylinder under the distribution of internal pressure indicated in Figure 3 can be at once expressed in terms of the radial distortion of the same cylinder under the same internal pressure distributed along the whole of one semi-infinite axis as shown in Figure 4. If we assume for the latter that the radial displacement at a

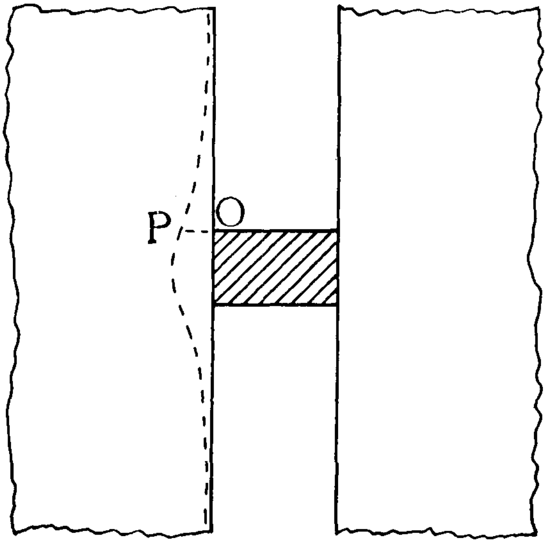

FIGURE 3. The dotted line indicates qualitatively the nature of the radial stretch at the internal wall under an internal pressure applied over the shaded region.

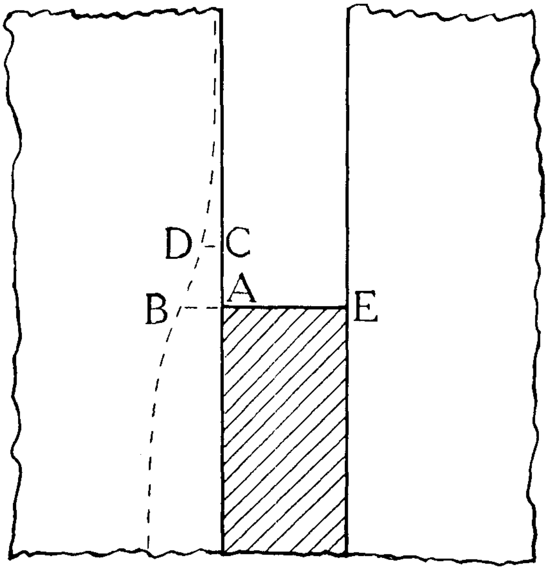

FIGURE 4. The dotted line indicates qualitatively the radial stretch at the internal wall under an internal pressure applied over the shaded region.

point on the axis situated at a distance of one radius from the end of the region where the pressure ceases is one half the displacement at the place where the pressure ceases (that is, if in Figure 4 $DC = \frac{1}{2} AB$, where $AC = \frac{1}{2} AE$), a not unplausible assumption, then in Figure 3 the radial displacement OP is approximately 0.35 what it would be at the corresponding point in Figure 4. This makes the correction on the effective cross section of the piston 0.40 per cent at 25,000. The final correction for the cross section was taken as 0.5 per cent at 25,000. The uncertainty in the final result arising from uncertainty in this correction should not be more than 0.2 per cent at the most.

The correction can be calculated from the dimensions of the cylinder and the elastic constants with the simplifying assumptions that the cylinder is infinitely long and exposed to internal pressure over its entire internal length, that the external figure can be taken as cylindrical with the mean external radius instead of tapering as it actually is, that the external pressure can be taken as uniform over the entire external infinite length, and that the longitudinal compressive stress arising from the thrust which forces the taper into its external collar in order to generate the external pressure is uniform along the axis. With these assumptions the calculated internal radial displacement comes out two thirds of that measured. The agreement is perhaps as close as could be expected in view of the extremely rough approximations that had to be made for the calculation. The effectiveness of the external support given to the pressure vessel is shown by the calculation to be very high, the radial enlargement under the actual conditions being only 0.26 of what it would have been if there had been no external support. Of course the uncertainty arising from the correction for distortion is correspondingly reduced, a great advantage of the method.

A further rough and presumptive check on the calculations was obtained by measuring with a simple mechanical contrivance the change of internal diameter while the cylinder was exposed to external pressure only by thrusting it into its collar. The change of internal diameter calculated with the same simplifying assumptions mentioned above was 83 per cent of the measured change.

THE MATERIAL FOR TRANSITION

The demands on a transition adapted to serve for a pressure fixed point are exacting; it must occur at the proper pressure, the transition must run rapidly and with large enough change of volume for easy manipulation with both phases present, the transition should start in either direction with the minimum amount of super- or subpressing, and there should be little or no region of indifference. This latter means that when the two phases are in contact at a fixed temperature, pressure should automatically come to a single final value, no matter whether that value is approached from above or below. This requirement of no region of indifference is automatically met when the phases are liquid and solid, as in the former method of calibration against freezing mercury, but it is a very restrictive requirement on the phase change of solids.

There were available for selection some 65 or 70 substances whose phase diagrams have been mapped out up to 50,000 kg/cm^2. Most of these may be summarily ruled out, chiefly on the ground of too great sluggishness of transition or too wide a region of indifference. Of the entire list only three were found sufficiently promising for further examination: Cu_2I_2 with a transition near 15,000; KCN with a transition near 20,000, and Bi with two transitions in the neighborhood of 25,000. KCN was tried, but proved too sluggish and also to have an appreciable region of indifference. Cu_2I_2 was not tried, the measurements with bismuth having in the meantime shown that the mercury and bismuth fixed points would be adequate, but I do not believe that if Cu_2I_2 were tried it would prove any more satisfactory than KCN. Bismuth proved much easier to handle even than freezing mercury, and seems satisfactory in every way. The measurements of the rest of this paper are based on the use of bismuth. If in the future it should be necessary for someone else to use some other transition it would be worth noting that in some cases the secondary properties of the transition are very sensitive to impurity, so that it is not inconceivable that highly purified Cu_2I_2 or KCN could be used.

DETERMINATION OF THE FIXED POINTS

Determinations of the transition pressures were made with three different pieces of apparatus. Two of these were not as favorable as the third; the measurements with them must be regarded as in the nature of checks. Most of the measurements were made with the apparatus already used for a variety of measurements to 30,000. This is shown in Figure 5. External pressure on the pressure vessel is produced by thrusting it into a tapered collar with a 6 inch piston. Pressure on

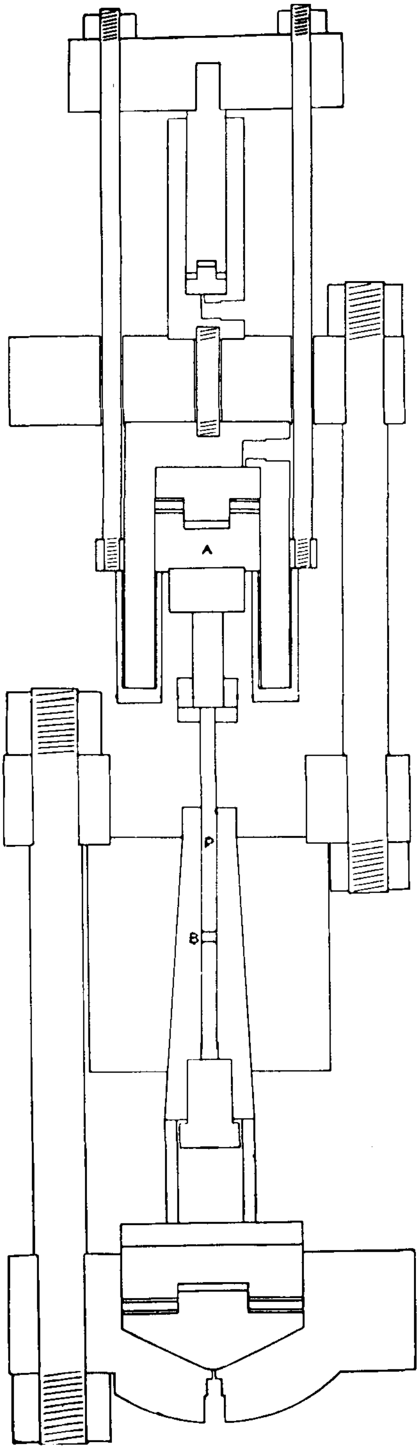

FIGURE 5. General view of the pressure apparatus. The bismuth undergoing transition is at B. In use the piston A is in a more extended position than shown, and the piston P is shorter.

the bismuth is produced by a 3.5 inch piston, driving a carboloy piston varying from 0.485 to 0.515 inches in diameter in the various set-ups. In order to be able to use the experimentally determined values for the correction to the cross section it is of course required that the external pressure on the vessel during the determinations of the transition be approximately the same as during the determination of the correction. This external pressure does not need to be controlled with high accuracy, however, and it was sufficiently good to measure the pressure on the 6 inch piston with a commercial Bourdon gauge of 15,000 lb/in^2 capacity. Friction on the outside of the cone could be allowed for by determining the displacement into the collar as a function of pressure, both with increasing and decreasing pressure. The pressure on the 3.5 inch piston driving the carboloy piston, on the other hand, has to be determined and controlled with the greatest possible precision. For this purpose the pressure on it was measured with a free piston gauge connected in series in the line between pump and press. The response of such a gauge to changes of pressure is always somewhat sluggish in spite of continual rotation of the piston, so that after every increase of pressure by operating the hand pump, or after every decrease by opening the valve, the pressure on the 3.5 piston would at first overshoot the mark, slowly creeping back to the final value as the piston gauge assumed control. Since the progress of the transition itself has to be judged by observing the creep, this effect might seriously lower the accuracy of the readings. It was avoided by providing a valve in the line between piston gauge and 3.5 inch piston, which was closed before every change of pressure, not being opened again until the piston gauge had become stationary. Even at constant pressure it was necessary to pump at intervals because of the unavoidable leak in the piston gauge. These intervals were made longer than they would have been otherwise by attaching a chamber of considerable capacity in the line, the volume compression of the liquid in this chamber providing a reservoir partially neutralizing the leak at the gauge. By this means the necessary pumping intervals were made longer than the intervals necessary to discover the direction of the transition, so that there was no complication on this score if the manipulations were properly made.

The bismuth had been highly purified by double electric deposition, and had furthermore been mechanically filtered in the liquid state and slowly crystallized.

The procedure in determining the transition pressure was first to increase the pressure in large steps on 3.5 and 6 inch pistons simultaneously, making rough measurements for orienting purposes of piston displacement and of the displacement of the pressure vessel into its collar. From this latter the friction could be calculated and thus a check made that such an external pressure had been attained as was required to duplicate the conditions during the measurements of the bore correction. Having arrived at the approximate pressure of the transition, the external pressure was kept constant by maintaining the pressure on the 6 inch piston constant, and the further manipulations were made only with the pressure on the 3.5 inch piston, the changes of which were slight. Pressure was now increased in small steps of approximately 400 kg/cm^2 on the bismuth, until the transition had started to run, as shown by the rapid piston displacement on the 0.0001 inch gauge. The total piston displacement corresponding to complete running of the transition was approximately known from previous work. The transition was allowed to run until it was one third or one half complete, and then pressure was lowered by 400 kg/cm^2, the transition then ceasing to run. Pressure was now increased again in steps of 80 kg/cm^2 (on the bismuth), pressure held at each point for three minutes, and the piston displacement noted during these three minutes as a function of time. There is always some creep after every change of pressure; the transition is shown by a larger creep which does not slow down with time. Having thus located the transition with increasing pressure, the reverse process was performed, giving thus a location of the transition with decreasing pressure to the nearest 80 kg/cm^2. With a little practice three minutes was sufficient to adequately characterize the creep and definitely establish the presence or the absence of the transition. The mean of increasing and decreasing determinations was taken as the transition pressure.

The ratio of the difference between increasing and decreasing pressure to the total mean pressure was defined to be the "total friction"; it includes ordinary mechanical friction and the natural width of the "band of indifference." The total friction varied considerably in the different set-ups. The minimum value was 2.9 per cent—this sets an upper limit to any possible region of indifference. The width of the region was established with much greater accuracy during the calibration of the manganin gauge, to be described presently. The question of whether the pressure determined by taking the mean of the increasing and decreasing pressures is the pressure of true thermodynamic equilibrium is after all of minor importance; the important point is how reproducible the mean is, and this question is answered by the consistency of the results with different set-ups. The results are summarized in Table I.

Rough check measurements were made with two other pieces of apparatus. One of these was the regular apparatus in which compressibilities are being measured to 50,000, to be described in fuller detail in another paper. The piston diameter of this is only 0.260 inch. The distortion correction was determined by calculation, allowing as well as possible for end effects, and at 25,000 was 1.35 per cent on the cross section. The other apparatus was a preliminary one of 0.40 inch diameter, which had been used in checking the effectiveness of giving external support to the cylinder by making it conical and pushing it into a collar. The external support in this apparatus was produced automatically by the thrust of the

TABLE I

PRESSURES OF THE I–II BISMUTH TRANSITION

30°

Diam. of Piston inches	Total Friction Per Cent	Pressure kg/cm^2
.4934	5.1	25,430
.5332	9.0	25,465
.5334	4.1	25,400
.4918	4.0	25,450
.4958	7.4	25,380
Weighted mean		25,420

75°

Diam. of Piston inches	Total Friction Per Cent	Pressure kg/cm^2
.5334	2.9	23,420
.4918	4.3	23,330
.4958	11.2	23,160
Weighted mean		23,350

high pressure piston, and not independently. The external support on this is much less than with the two others, the external pressure being only 0.105 of the internal pressure, so that the correction for distortion is much larger. This correction was calculated to be 2.5 per cent for the middle of an infinite cylinder with the same simple assumptions as those already mentioned. This is to be reduced by an uncertain amount due to two end effects. Probably multiplication by a factor of one half is the best that can be done to allow for these end effects. The transition pressures found at 30° in this way with the 50,000 apparatus and with the early apparatus were 25,880 kg/cm^2 (total friction 8.2%), and 25,620 kg/cm^2 (total friction 4.5%) respectively. The agreement can probably be regarded as satisfactory in view of the more unfavorable dimensions of these two other forms of apparatus, and the larger calculated corrections.

In addition to the transition between the forms I and II, which is the one which has been just studied, bismuth has another transition between the forms II and III at pressures not much higher than I–II. With proper care the II–III point might also serve as a fixed point. The manipulations are somewhat less convenient, however, because in the first place the transition I–II has to be got out of the way before II–III can be measured, and the two transitions are so close together that this offers some inconvenience, and in the second place the volume change II–III is only two thirds that of I–II. I did not attempt therefore any determination of the transition II–III with an accuracy sufficient for calibration purposes, but I did make measurements with a single set-up with the good apparatus and obtained the following results: At 30°, 26,960 kg/cm^2 (total friction 4.5%); and at 75°, 25,850 kg/cm^2 (total friction 3.1%).

THE MANGANIN GAUGE

The fixed points having been established, the manganin gauge can be calibrated in terms of them. Two such gauges have been calibrated at this writing, wound from wire from the same spool. The manganin was of American origin, obtained from the Driver Harris Co., of 0.0035 inch diameter, double silk covered, wound non-inductively into coreless toroids of about 70 ohms resistance. Similar coils were used in measurements previously published of resistance to 30,000, pressure being obtained by linear extrapolation from the 7640 kg/cm^2 mercury point. The coils were seasoned by exposure for 8 hours per day for 6 days to a temperature of 140° C. with an interlude of 1 hour each morning at liquid air temperature, and also by several applications of 30,000 at room temperature. In general, the zero of these two coils has been noticeably more constant than that of other coils used in previous work to lower pressures.

The first coil was calibrated at room temperature (23° C.) against freezing mercury at 0° C. (7640 kg/cm^2) in the apparatus with which most of my measurements to 12,000 have been made. In this apparatus the upper cylinder in which the coil is located is at room temperature, while the lower cylinder, containing the mercury, is at 0°. After this calibration the coil was transferred to the 30,000 apparatus, in which was placed a cylindrical slug of the same electrolytic bismuth as that whose absolute transition pressure was determined above, weighing about 28.5 gm. The rest of the 30,000 container was filled in the regular way with iso-pentane, which is known not to freeze at 30° below 30,000. From previous measurements the approximate transition pressure and the displacement of the piston to be expected during the transition were known. To facilitate following the progress of the transition the displacement of the piston was read with an Ames dial gauge graduated to 0.001 inch. The procedure was to raise pressure nearly to the transition point, wait for thermal and other equilibrium, then increase pressure sufficiently to start the transition, which was then allowed to run about one half to completion, as indicated by the piston displacement. Pressure was now reduced to such a value that there was no secondary reaction. From here as a starting point, and with the transition known to be one half completed so that the two phases were certainly in contact with each other, pressure was raised until it started to creep back perceptibly. This creep was allowed to continue until it had sensibly stopped, which might take from 10 to 15 minutes. The pressure reached in this way was called the equilibrium pressure from above. Pressure was next lowered until it started to creep up again, and in a similar way an equilibrium pressure from below was obtained. The mean of these two was taken as the equilibrium point. These two pressures differ by at least the true width of the region of indifference, but may differ by more than this because of sluggishness of the transition. If the width of the region of indifference were being determined for itself a different procedure would be adopted. However, since pressure is here transmitted by a liquid, the pressures reached from above and below should not differ because of any factor of solid friction, and in fact the two pressures found with the manganin gauge calibrations are much closer than in the absolute determination of the transition pressures already described.

The first coil was calibrated against the bismuth I–II transition in this way at 26°, 30°, and 75°. The points at 7640 being already known from the measurements with freezing mercury (the 7640 point at 75° had to be obtained from previous measurements of the temperature coefficient), it was then possible to construct a second degree formula, giving pressure as a function of the measured displacement of the balancing point on the slide wire, reproducing the known points at 7640 and 25,000. If the relation were exactly linear, assumed in previous work, the second degree term would of course vanish. It did not vanish, but was small. At 30° the pressure of the bismuth point obtained by linear extrapolation from 7640 was 25,010 against 25,420 actual, or 1.6 per cent too low, and at 75° the figure was 23,120 against 23,300, or 0.8 per cent too low. The deviation from linearity is thus in an abnormal direction, shown by no other pure metal or alloy except single crystal antimony over a limited range.

The procedure in calibrating the second coil was somewhat different. In the first place, the 7640 point was experimentally determined at both 30° and 75° in order not to have to rely on the temperature coefficient determined on another sample. The 7640 point was determined in two steps. First, the 7640 point at room temperature of a coil of German manganin 0.0055 inch in diameter, such as had been used in all my early work to 12,000, was determined against freezing mercury at 0° in the regular way. The constant of this coil having been thus determined, the 30,000 coil was then compared against it at two temperatures, the German coil being kept fixed in one cylinder at room temperature, and the 30,000 coil in the other cylinder, which was thermostatically maintained first at 30° and then at 75°. The two coils were compared against each other at intervals of 2000 kg/cm^2 over the pressure range up to 12,000. The ratio of the resistance changes of the two coils proved not to be a constant, but there is a slight drift with pressure. A smooth curve was drawn through the points thus found, and the coefficient of the 30,000 coil at 7640 was taken from the curve.

The 30,000 coil was next transferred to the 30,000 apparatus for calibration at the higher points. The arrangements for this were modified as compared with those of the first calibration. The amount of bismuth was cut in two, and the space thus made available was filled with a thin walled steel shell containing mercury. In this way both mercury freezing points and bismuth transition points could be determined with the same apparatus. It was not feasible to cool the 30,000 apparatus to 0°; otherwise a single set-up could have been employed for the complete calibration. With this arrangement the mercury and the bismuth points were determined at 30° and 75°. The freezing pressures of mercury at these two temperatures are approximately 13,700 and 23,000 kg/cm^2. If the 13,700 point were accurately known, the 7640 point could be dispensed with. Theoretically, this point should be known from previous work, since the previous calibration of the manganin gauge against the free piston gauge had been made up to 13,000. Actually, however, the 7640 point was determined more carefully and a number of times, so that more confidence can be placed in it than in a value just beyond the previous range, it being well known that error is likely to pile up near the end of a range. At 75° the mercury point is in new territory, and is very close to the bismuth point; the determination at 75° is therefore to be taken in the spirit of a determination of a new fixed point.

At 30°, the bismuth point extrapolated linearly from 7640 was 24,910 instead of 25,420, or 2.0 per cent too low, against 1.6 per cent with the first coil. At 75° the linearly extrapolated bismuth point was 22,920 against 23,300, or 1.6 per cent too low, against 0.8 per cent of the first coil. This indicates that the departure from linearity of pieces of wire from the same spool may vary, just as the absolute constants are known to vary. The 7640 constant of the second coil was 0.6 per cent greater than that of the first one. This means that for the [illegible] accuracy a two point calibration for every individual coil will be necessary. It would be too early to draw the conclusion that in general the greater departure from linearity goes with the greater first degree coefficient.

Two determinations at 30° of the bismuth point of the second coil on successive days gave identical results to the limit of sensitiveness of the readings, better than one part in 6,000. Determinations of the bismuth and mercury points at 30° at an interval of two months gave an increase of 5/6000 of the bismuth point and 9/3700 for the mercury point. Taken at its face value, this would indicate a considerably larger secular change in the second degree term than in the first degree term, but it would be too early to draw this conclusion in general, because of the uncertainty in the bismuth point due to the region of indifference.

As a further indication of the variation in magnitude to be expected in the second degree term for different grades of manganin may be mentioned the results of the calibration up to 12,000 of the 30,000 coil of American manganin against the coil of German manganin. The ratio of the change of resistance of the first to that of the second varied approximately linearly with pressure from an initial value of 1.694 to 1.679 at 12,000. The interpretation of these results is that the second degree term in the German manganin is of the opposite sign from that of the American, the numerical value being such that a linear extrapolation by the German manganin from 7640 to 12,000 would be in error by 0.4 per cent at 12,000.

At 30° the measurements with the two coils gave values for the width of indifference for bismuth I–II varying from 60 to 100 kg/cm^2, and at 75° from 15 to 50. The lower of these values are to be taken respectively as upper limits for the true width of the region of indifference. In contrast to the bismuth points, the mercury points showed no perceptible region of indifference at all, the sensitiveness of the measurements being about 3 kg/cm^2. This is to be expected because of the different dynamics of a solid-liquid transition as compared with a solid-solid transition. In any event it affords a check on the sensitiveness of the method.

The following values were obtained for the melting pressure of mercury: at 30°, 13,700 and 13,730 kg/cm^2, and at 75°, 22,950 kg/cm^2. At 30°, the value of my former measurements, obtained by a slight extrapolation, was 13,610. At 75° I have already published[3] the va[illegible]570 obtained by a linear extrapolation of [illegible]nin gauge. Correcting this by 1.6 per cent for lack of linearity of the manganin as determined above, gives 22,930, practical agreement with the present value. Extrapolation of my previous values from 20°, assuming a second degree relation in the temperature with the constants so chosen as to agree with the measurements in the range from 20° down to the atmospheric melting point, gives 22,600 at 75°. The melting line thus appears to have very slight curvature, but it continues in the normal direction over the entire range up to 75°. This is of some interest, because except for water, this is the highest pressure to which any accurate determinations of the melting parameters have been made. The curvature of the melting curve of water was also found to be normal, that is, the curve is concave toward the pressure axis.

Before the method of using the transition of bismuth to give fixed points was adopted, I made various attempts to calibrate the manganin gauge directly from measurements of the force driving the piston. This method was eventually abandoned in favor of the method above because it appeared that the friction on a piston packed to prevent leak of a liquid must always be greater than the friction of a piston packed against leak of a soft metal like bismuth. However, if the other better method had not offered itself, it would doubtless have been possible to obtain fairly satisfactory results by sufficient repetition of this method, since the curves with rising and falling pressure were surprisingly reproducible with different set-ups. The total friction with this method was 24 per cent at 25,000 and was rapidly becoming greater, so that I did not try for higher pressures. The measurements by this method showed the same abnormal departure of the resistance of manganin from linearity in pressure, and roughly of the same magnitude, between 1 and 2 per cent at 30° at 25,000, as by the better method above. It is worth while to have confirmation by this more direct method, even although the accuracy is lower.

I am indebted for financial assistance in this work to the Rumford Fund of the American Academy of Arts and Sciences and to the Francis Barrett Daniels Fund of Harvard University.

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[3] First reference under (2), p. 192.

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THE LINEAR COMPRESSION OF IRON TO 30,000 kg/cm^2

BY P. W. BRIDGMAN

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THE LINEAR COMPRESSION OF IRON TO 30,000 kg/cm^2

By P. W. Bridgman

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Introduction

I have already published[1] measurements of the linear compression of a number of substances up to 12,000 kg/cm^2. Apparatus has now been developed by which this range can be extended to 30,000, and I am now starting a program of measurement of linear compressions in this higher range. There are two necessary preliminaries to such a program. The first is the establishment of the pressure scale by the establishment of pressure fixed points and calibration of secondary pressure gauges. This work has already been done and is being published. The second is the measurement of the absolute compression of some substance of reference; this is the task undertaken in this paper. This task is necessary because the method adopted for the measurement of the linear compression of most substances is a differential method—measurement of the difference of compression between the substance in question and a standard. Measurement by difference is used because it is very much more convenient and rapid, although it would be possible to measure the actual compression of many substances by the same method as that used here for the standard substance. As in the previous work, the standard substance is chosen as pure iron.

Method

The general features of the method are the same as before,[2] namely the change of length of a rod of iron is measured relative to the pressure vessel, and this relative measurement is converted into an absolute measurement by an independent and simultaneous measurement of the distortion of the pressure vessel. The whole experimental set-up is, however, so different from that used before that a fresh description of many of the details is necessary. The pressure apparatus now has to be in a single piece, separate pressure chambers connected by tubing no longer being feasible; this results in a much decreased length of the specimen with corresponding loss of sensitiveness. The length was less by a factor of about 5. However, the chief interest in pushing the results to a higher pressure range is in the departures from linearity. Other things being equal, the accuracy with which the second degree term in the pressure can be determined increases as the square of the range. The range is here increased by a factor of 2.5 ($=\sqrt{6.25}$), thus somewhat overbalancing the unfavorable factor arising from decrease of length.

The method by which the change of length of the iron rod relative to the pressure vessel was measured is practically the same as that used before.[2] A shoulder on one end of the rod is kept pressed by a stiff spring against a shoulder in the pressure vessel. A high resistance wire is pressed against the other end; this resistance wire slides over a contact fixed to the pressure vessel. Potentiometer measurements of the effective resistance of the wire, made on a potentiometer in the way already extensively used and described, give, after suitable reduction, the mechanical motion. The arrangement is shown in Figure 1.

The arrangement by which the change of length of the pressure vessel was determined had to be materially altered from that used before because of the drastic difference in the arrangements. Formerly the pressure vessel was a long geometrically perfect cylinder, and the change of length was measured with an optical magnifying device between points on the outside opposite the ends of the iron rod. But now the pressure vessel was conical in shape, and it was subjected to external pressure by being pushed into a heavy conical collar. The points on the exterior of the pressure vessel opposite the ends of the rod were therefore inaccessible. Even if these points had been accessible, measurement of the change of external length would probably not have been particularly pertinent because the proportions were such that appreciable warping of the cross section may be anticipated. Under the circumstances it seemed that the best that could be done was to determine the change of length of the vessel from two probe holes, drilled approximately parallel to the axis, as shown in Figure 2. These holes were ⅛ inch in diameter, and were situated about 0.5 inch from the axis, giving therefore about 0.25 inch of solid wall between the hole and the inner bore. So close to the center as this, warping would be expected to be very much less than at the exterior, since near the axis the warping must be of the second degree in the radial distance.

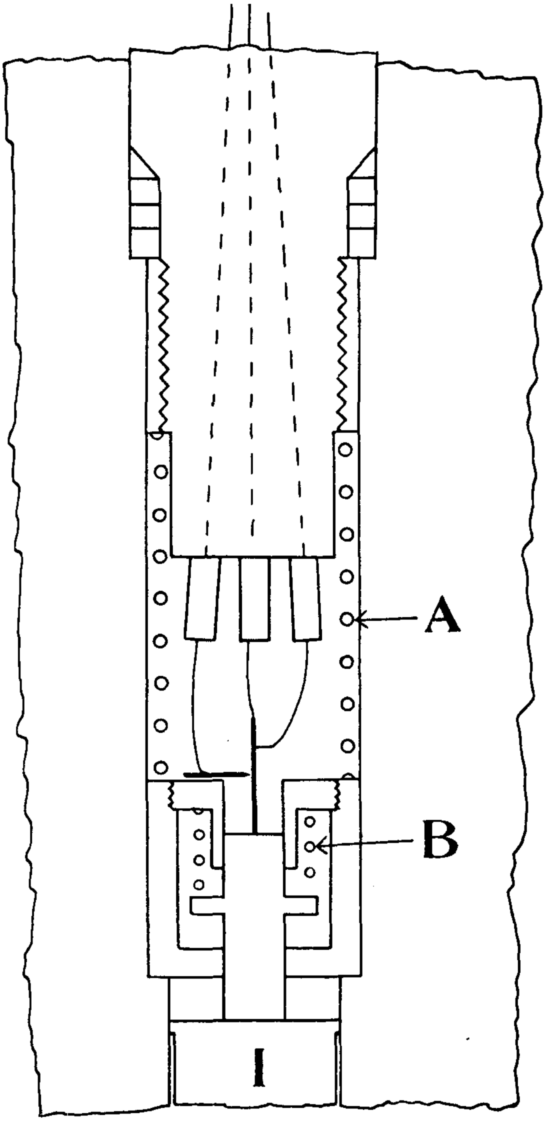

FIGURE 1. The sliding contact arrangement for measuring the change of length of the iron rod I with respect to the pressure vessel.

Apparently the cylinder was not appreciably weakened by the presence of these probe holes. One might have anticipated either an increased danger for the cylinder to rupture by splitting, or else a possible collapse of the holes under the external pressure, but neither effect was found. No permanent change of dimensions of the holes could be detected after use. The probe rods had a clearance for most of their length of 0.010 inch, but where they emerged from the cylinder they were fitted with collars with clearance of only 0.0005 inch in order to reduce play. The lower ends of the probe rods were bevelled at 60°, and the very ends rounded to spheres of small diameter and hardened. A sharply pointed depression in the cylinder to receive them was made with a punch. The relative longitudinal displacement of the probe rods was transferred for measurement to two heavy iron bars, bent as shown in Figure 2, and the relative motion of these bars ultimately determined with an Ames dial gauge, as indicated, graduated to 0.0001 inch. The weight of the bar for the lower probe was entirely taken up by a counterweight with ball bearing pulley, and the bar itself was pressed into firm contact with the probe by a spring, not shown in the figure, thrusting directly in the line of the probe. Contact of the other bar with the upper probe was maintained by the weight of the bar (about 2 kg.), which was not counterbalanced in any way. Three point contact between the two bars was maintained by steel balls rolling in polished V grooves or over polished flats in an obvious enough fashion. The bars were maintained vertical against the tendency of the weight of the upper bar to fall toward the left by a horizontal cord several meters long acting toward the right at the point A.

This elaborate and somewhat clumsy arrangement was made necessary by the exigencies of construction of the press, by the fact that there is a total vertical displacement of the pressure vessel during the run of nearly 0.5 inch as it is forced into its supporting collar, and by the desirability of some sort of arrangement that could be immersed into the temperature bath along with the entire press to permit measurements at higher temperatures. Before this final arrangement was adopted a simpler but less satisfactory scheme of take-off from the probes by a lever arrangement was tried.

The maximum relative displacement of the ends of the probe holes was about 0.00400 inch, in the direction of an extension with increasing pressure. This extension therefore makes the shortening of the iron bar relative to the pressure vessel too large, so that the correction to the relative shortening is subtractive. The longitudinal correction is about one quarter of the measured relative shortening. An error of 0.00001 inch in the longitudinal shortening of the cylinder, which was the limit of sensitiveness of the Ames gauge, corresponds there-

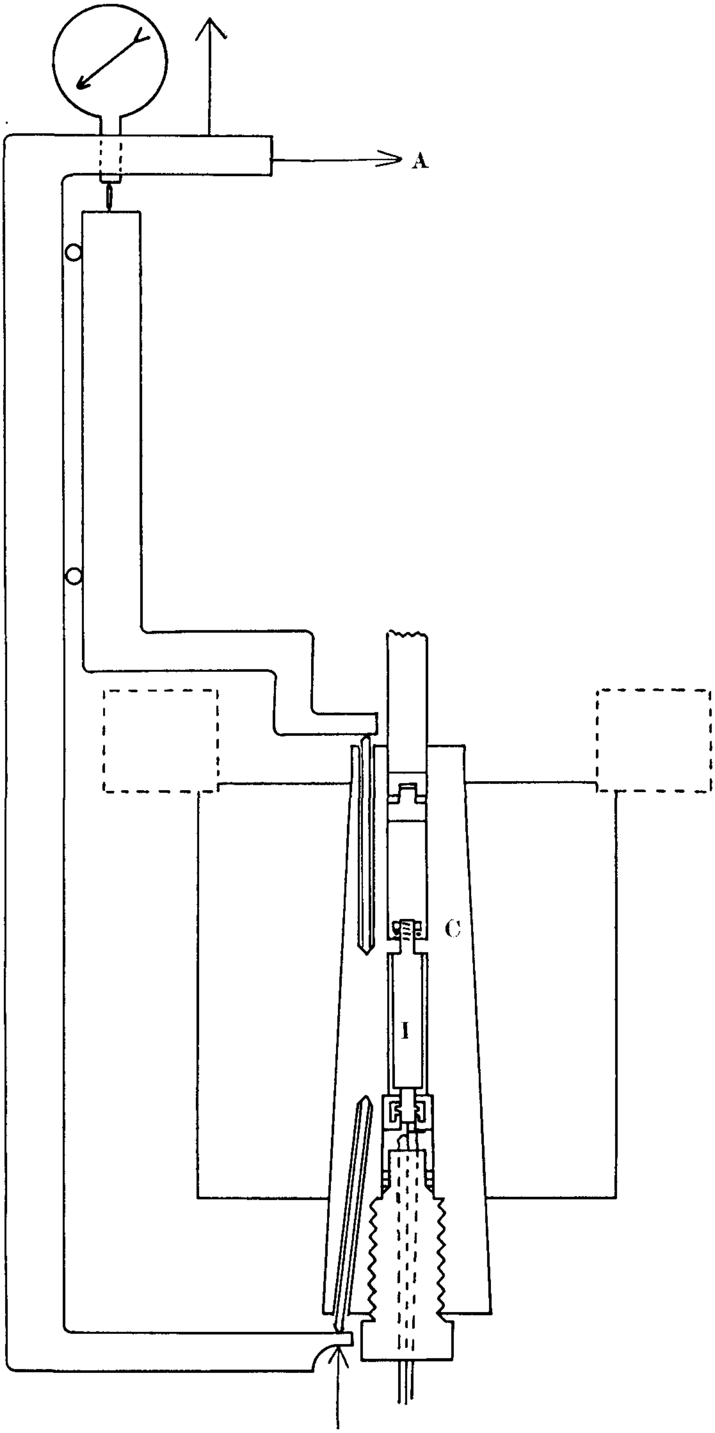

FIGURE 2. General assembly, showing the iron rod I mounted in the pressure vessel C.

fore to an error of 1/1200 in the final result. The sensitiveness of measurement of relative shortening of rod and pressure vessel may be pushed considerably higher by suitably choosing the electrical constants, so that the limiting error, as far as sensitiveness of reading goes, is set by the longitudinal factor.

The measured longitudinal distortion of the vessel is a resultant of several factors, of which the largest are probably internal pressure, external pressure, and longitudinal compression arising from the action of the pressure thrusting the vessel into the external conical collar. These three stresses are not simply related to each other, and the resultant is complex. Since the correction determined by these factors is one third of the final result, and is doubtless the factor limiting the accuracy of the final results, it will pay to discuss it in some detail. By far the largest of the three component effects just mentioned is that due to the external pressure on the vessel due to the thrust into the supporting collar. This effect is naturally an extension with increasing pressure. The effect of internal pressure is on the other hand a shortening. The third component, longitudinal compression due to the thrust, may be shown by simple calculation to be small at the most. Only the roughest qualitative calculation can be made of this, because this compressive thrust is variable along the length of the vessel, having its full value at the bottom, and dropping to zero, in a way not easy to specify exactly, at the top. The two main components in the distortion do not vary in a simple way over the pressure range. With increasing pressure, internal and external components both vary linearly and the resultant total extension is also approximately linear. But with reversal of direction of change of pressure on reaching the maximum, the component due to internal pressure at once starts to reverse itself, whereas external pressure remains constant for a while in virtue of friction in the collar, in spite of the decrease in longitudinal thrust. The result is that the net longitudinal extension continues to increase when pressure starts to drop, reaches its maximum between 20,000 and 25,000, and gives a hysteresis loop of the general form indicated in Figure 3. The amount of external friction and therefore the external pressure can be determined with fair accuracy from the measurements, which were always recorded, of the longitudinal displacement of the pressure vessel into the supporting collar. Given the external and internal pressure it is then possible to reproduce, with an error of perhaps 5 per cent, the longitudinal distortion by a linear expression in these two pressures.

A check can be obtained on the measurements of longitudinal distortion by measuring the relative motion of rod and vessel when external pressure only is applied. In this case there is no change of dimensions of the rod, so that the potentiometer measurements should agree exactly with the distortion measurements. Of course this could be done only over a comparatively small external pressure range, because the maximum external pressure with no accompanying internal pressure would have collapsed the vessel. The range of external pressure for this check was taken as about one half the maximum of the regular runs, corresponding to about 6,000 kg/cm² external (12,000 during regular run). The uncorrected results of the check made in this way were not good; the relation was not linear, there was hysteresis, and different set-ups gave different results. The extension measured by the potentiometer varied on three set-ups from 6 to 17 per cent greater than that measured at the probe holes. The irregularities are probably due at least in part to irregularities in the external friction. There are two conceivable reasons for the discrepancy, granting that the measurements themselves are correct. The

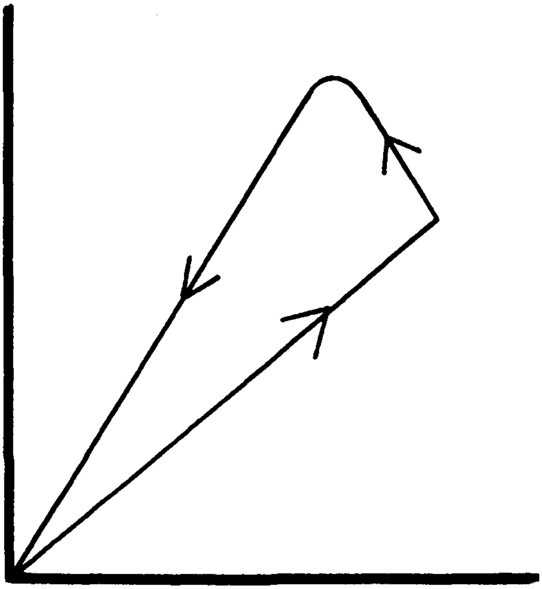

FIGURE 3. Showing the general nature of the hysteresis loop in the relation between internal pressure (abscissas) and elongation of the pressure vessel measured at the probe holes (ordinates).

first of these is warping of originally plane sections of the vessel, different in amount at the two ends. Under the conditions of these check measurements it is difficult to estimate even what the sign of this would be, but it would seem that its magnitude must be small. The second and the more important possibility is concerned with the fact that the lower probe hole is not parallel to the axis, but is inclined to it at an angle of 8.15°. This is a bad feature of the design that was recognized in the beginning, but the geometrical restrictions imposed by the rest of the apparatus made it almost impossible to avoid. If the angle 8.15° changes during the extension there is a resolved component along the axis which contributes to the measured longitudinal displacement. It is not difficult to get an approximate numerical value for the magnitude of this effect. In the first place there is the formula of elasticity theory for the ratio of the radial displacement at the radial distance r_a to that at the interior wall r_i in an infinitely long cylinder under external pressure only:

$$\frac{u_{r_a}}{u_{r_i}} = \frac{r_a}{r_i} \, \frac{\dfrac{1}{\lambda+\mu} + \dfrac{r_i}{r_a}\dfrac{1}{\mu}}{\dfrac{1}{\lambda+\mu} + \dfrac{1}{\mu}}$$

The external radius does not enter this expression. Taking $r_a = 1.20$, and $r_i = 0.57$, and for the elastic constants $\lambda = 9.4 \times 10^{11}$ and $\mu = 7.7 \times 10^{11}$, this gives $u_{ra}/u_{ri} = 1.35$. Now u_{ri} is accessible to direct measurement; this was done with a simply constructed bore measurer under the same conditions of external pressure. It should also be possible to calculate u_{ri} directly from elasticity theory, assuming an infinitely long cylinder. The value calculated in this way is 15 per cent less than that directly measured, giving a good enough check considering the crudity of the approximation. u_{ri} now being known, u_{ra} can be at once calculated. To the u_{ra} found in this way a small term amounting to 11 per cent is to be added for the radial expansion of the bottom of the cylinder under the thrust which generates the external pressure. The resolved component of this along the axis can now be obtained, with the result that the longitudinal extension of the vessel measured with the probes corrects up to a value only 1 per cent less than that measured with the potentiometer directly on the inside, giving essentially a check, considering the irregularities. The outstanding discrepancy of 1.0 per cent might be argued to be due to warping of the cross section. This discrepancy of 1.0 per cent is on a correction of 25 per cent to the measured change of length, so that the maximum possible error in the final result that can be ascribed to warping is .25 per cent. Even this small possibility of error is much reduced by the procedure adopted for reducing the final observations, as will be explained below. This check gives confidence in the soundness of the calculation of the correction for change of inclination of the lower probe rod. Under the conditions of the pressure measurement, this correction is much less than above, where the pressure was external only and the conditions as unfavorable as possible, for in the actual experiment the radial displacement is much less than above because the internal pressure to a large extent neutralizes the external pressure. A correction of 0.53 per cent was applied to the final compressibility for this effect.

The mounting of slide wire and contacts has already been shown in Figure 1. The wire was of "Nichrome IV," about 0.013 inch in diameter, with a resistance of about 0.13 ohms per centimeter. The total relative motion was about 0.046 cm, corresponding to a change of resistance of 0.0060 ohms. The constants of the electrical circuit were so chosen that this gave about 50 cm displacement of the slider of the potentiometer. This could be read to 0.1 mm, or 1 part in 5000. So high a sensitiveness was greater than could be used because of the irregularity of the readings, which at the best amounted to 10 times as much, and usually was much more.

The slide wire was calibrated by measuring on the potentiometer the change of resistance for known displacements. The displacements were produced by a screw in an arrangement of obvious enough design, and the the amount of displacement was measured with an Ames 0.0001 inch gauge, which itself was calibrated against standard gauge blocks. The potential and current leads were of pure nickel, 0.008 inch in diameter, attached by electric welding by the discharge from a condenser of suitable capacity charged to 110 volts. In the previous work to 12,000 kg/cm^2 the terminals had been attached by soft soldering, but in this new high pressure range of 30,000 soldered connections had been sometimes observed to crack because of the high differential compression. Such cracks, even if the connection were not absolutely broken, might introduce irregularities because of indefiniteness of the point of effective contact. In fact the results did show a notable improvement in regularity after changing from soft solder to the weld.

The correction for the change of resistance of the slide wire under pressure over the entire range up to 30,000 was determined by direct measurement on a piece of wire contiguous in the original length to the piece used for the slide. This piece was 6 cm long, and 4 cm between potential terminals. The change of resistance proved to be linear with pressure over the entire range, with a maximum deviation of any single observed point from a straight line of about 1 per cent of the maximum effect. The coefficients were: at 30° $\frac{1}{p}\frac{\Delta R}{R(0,30°)} = -6.55\times 10^{-7}$, and at 75° $\frac{1}{p}\frac{\Delta R}{R(0,75°)} = -6.62 \times 10^{-7}$. The correction to the measured change of resistance arising from the change of resistance of the slide wire with pressure is 12 per cent, so that any error in the final result arising from uncertainty in this correction should be well below 0.1 per cent.

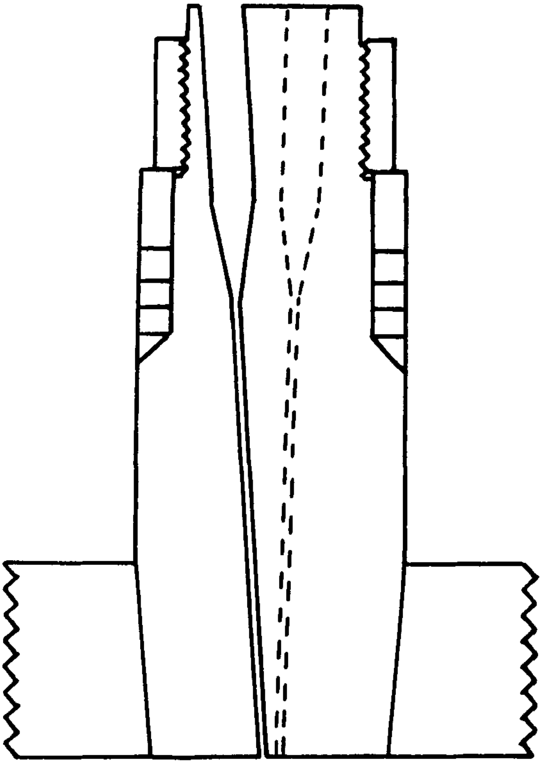

FIGURE 4. The blank insulating plug with packing rings.

The compressibility of the slide wire also enters as a correction into the final result. The various dimensions are such that the correction on the final result arising from this term is about 5 per cent of the *difference* of compression between nichrome and iron. Previous measurements, not published, up to 12,000 had shown that this difference is one per cent of the compression of iron itself. This was taken as sufficient justification for entirely neglecting this correction in the present work without further examination.

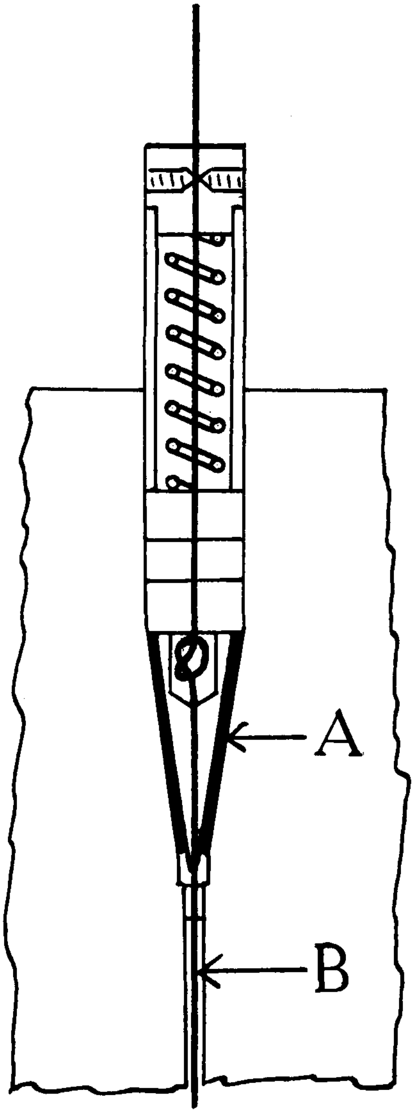

FIGURE 5. Detail of the insulating leads used in the plug of Figure 4.

In Figure 2 is shown the iron bar, I, mounted in the pressure vessel ready for measurement. It will be noted that three springs are used to keep the various surfaces in contact. Spring A (see detail in Figure 1) has to be materially stiffer than B, because B pushes against it. These two springs were wound out of piano wire of suitable diameter. At first the spring at C (Figure 2) was not employed, but the iron rod was held in contact with the shoulder on the pressure vessel by a solid nut screwed tightly home. However, various irregularities seemed to have their origin in differential distortion of the rod and the pressure vessel at this point. These irregularities were removed by putting a very stiff helical spring, milled from a solid piece of tool steel, between the nut on the rod and the shoulder on the pressure vessel.

During these compressibility measurements a much more satisfactory solution of the problem of electrically insulating the leads to stand these high pressures was arrived at than had been previously found. This had always been the limiting factor, since it takes much time to set up these insulating plugs and they used to fail either mechanically or electrically after one or two applications of the maximum pressure. Insulation is now provided by a cone of pipestone, A, only 0.005 inch thick, with an angle of about 15° (see Figure 5). The thickness is so small that the pipestone is prevented from shearing out by friction. The shearing stress in the pipestone diminishes exponentially along the length, so that at the apex of the cone, where the wire emerges, the stress is reduced to zero. There is therefore no tendency to blow out the fine piano wire lead, a great advantage over previous arrangements. This arrangement of the pipestone remains mechanically and electrically perfect for a number of applications of pressure. The angle is such that there is no disadvantageous sticking, and the cone can be removed and replaced without renewing the pipestone. The cone carrying the fine stem is of *mild* steel. The piano wire stem is knotted once to prevent pulling through. This scheme of knotting the lead wire was used at the Geophysical Laboratory a number of years ago, with fine copper wire, for a considerably lower pressure range. It would not be possible to knot a piano wire of much larger diameter than that used here, 0.013 inch. The knot on the wire in most of this work was buried in soft solder; this prevents it from cutting itself and also permits a longitudinal pull up to the breaking strength of the straight wire to be applied without cutting through at the knot. However, because of the relatively high differential compression at these high pressures, the solder has a tendency to pull away from the steel, permitting leak past the stem after a number of applications. Toward the end of this work the wire was silver soldered into the cone with better results. In the previous design leak was prevented by the principle of the unsupported area, the pressure in the soft packing being greater than that in the liquid. Now, however, the expelling thrust on the wire is done away with by the action of the cone, and leak has to be prevented by the natural resilience of the soft packing with no help from any differential stress. Fortunately the compressibility of rubber and "Duprene" is low enough so that if the washers are initially cut as large as is possible to crowd into the hole without folding there is still some excess natural diameter left at 30,000 to prevent leak. Special measurements of the compression of an equivalent grade of soft rubber gave a volume decrement of 27 per cent at 30,000 kg/cm^2, from which an idea can be obtained of the initial dimensions in the washer necessary to reach the maximum pressure without leak. However, when the washers are cut as large as they have to be to reach these high pressures, they are almost certain to fold and slip out of the hole unless some guidance is provided. This is done by the helical steel spring pressing down from above, as shown in Figure 5, the top part of the spring pushing against a stop clamped by a screw to the lead wire. Soft rubber and Duprene washers are used, the Duprene being on the side next the liquid to prevent the iso-pentane attacking the rubber, and the rubber doing perhaps the bulk of the packing because of its greater pliability. It is well to renew these washers after several applications of pressure, because they are likely to receive a set, which may lead to leak. Another improvement in the plug is the insulation around the fine stems where they come out through the plug. This was formerly of fine glass tubing, which was constantly breaking under the slight movements of the stems, and short circuiting. The glass is now replaced by silk; half a dozen turns of silk thread are wound around the wire at the mouth of the hole and these are then crowded to the bottom with a tube. The process is continued until the entire annular space, B, between stem and plug is filled with silk. No trouble has been experienced from short circuit in this location since this arrangement was adopted. One has to be sure that the silk initially is quite dry, and in assembling one has to avoid handling it with moist fingers.

It is of extreme importance that all particles of dirt should be eliminated on assembling the apparatus. As already mentioned, the maximum relative displacement is about 0.047 cm and the maximum deviation from linearity is about 0.0005 cm, so that an exceedingly small particle of grit between the bearing surfaces at any of the three crucial places may have a very large effect. The geometrical arrangement of the bearing surfaces was made as unfavorable as possible to the lodging of grit upon them, and all parts were cleaned before assembly by copious flushing with xylene and blowing out with an air blast.

Measurements, Calculations, and Results

More than twenty-five different set-ups were made and measurements made to 30,000 kg/cm^2 at room temperature. In spite of every effort it was not possible to get rid of capricious irregularities. There probably was no one cause of these, but many of the necessary conditions of the experiment were favorable to such irregularities. Friction cannot be expected to be exactly reproducible, and the steel vessel, continually strained as it is beyond the elastic limit, would be expected to show irregular hysteresis and creep. There seemed nothing to do except to attempt to eliminate the effect of such capricious irregularities by a large number of observations.

In marshalling the measurements a procedure was adopted calculated to eliminate any systematic error due to one effect hitherto not adequately discussed, namely warping of the cross section as a result of which the apparent change of length of the vessel measured at the probe holes is different from that at the interior where the rod is situated. It is evidently only differential warping at the two ends of the rod that is harmful. Warping may arise from various departures of the conditions from those in an infinitely long cylinder with internal pressure along the entire axis. One such effect arises at the two ends, where the internal pressure ceases at the upper and the lower plugs. This effect, however, is probably negligible because the plugs are several diameters removed from the critical region. It would seem that by far the most effective source of warping is tangential drag along the axis arising from friction at the outer and inner surfaces of the vessel. At the outer surface there is such a frictional force when the vessel is forced into its supporting cone, and at the interior there is such a force due to the friction of the moving plug with which pressure is generated. These effects, being different at the two ends, will produce just that differential warping that is especially to be avoided. This warping reverses sign when the direction of friction changes, and therefore reverses when the direction of motion of the moving plug or of the vessel into its cone reverses. The existence of the effect may be demonstrated experimentally by just reversing the direction of motion of the moving plug or of the vessel into its cone at approximately constant values of internal and external pressure. The maximum magnitude of this warping effect amounts to about 1 per cent of the total effect at the maximum pressure. During increasing pressure the effect will be in one direction and during decreasing pressure in the other. It should be eliminated by taking the mean of runs with increasing and decreasing pressure.

These considerations controlled the manipulation of the results. Readings were made at 13 approximately equally spaced pressure points, that is, at 0, 2,500, 5,000, 7,500, etc., both with increasing and decreasing pressure. The change of length of the iron rod was then calculated for each of these measurements, making all the corrections. These results for all the runs were then plotted, in one diagram for the measurements with increasing pressure and in another for those with decreasing pressure. The more discordant of the points at each of the 13 mean pressures were discarded; in a few cases as many as one third of the points were thus discarded, but usually about half as many. The remaining points were averaged, giving 13 approximately equi-spaced points for increasing pressure and 13 for decreasing pressure. A straight line was then passed by calculation through the initial and final points of each of these two groups, and the deviation from linearity, $\varDelta$, of the intermediate points calculated. A second degree curve in the pressure of the form $\varDelta = a + bp + cp^2$ was then passed by least squares calculation through these deviation points, weighting each point according to the component number of observations which had been retained in the average. In this least squares calculation all 13 points with increasing pressure were retained, but the two highest points with decreasing pressure were not used, for the reason that friction had not entirely reversed itself at these points so that the warping could not be expected to have assumed the value characteristic of decreasing pressure. The total number of component observations used with increasing pressure was 154, and 172 with decreasing pressure. The "standard error of estimate" $\sqrt{\Sigma d_i^2/n}$ of the points with increasing pressure was 0.36 per cent of the total change of length at the maximum pressure, and of the decreasing points 0.26 per cent. The average of the least squares deviation curves for increasing and decreasing pressure was then combined with the expression from which the deviations had been calculated, to give the final result. The deviation from the straight line of the midpoint of the curve joining initial and final points was 0.92 per cent of the maximum.

The linear term in the final result that would have been calculated from the increasing points differed by only 1.2 per cent from that which would have been calculated from the decreasing points only. The second degree term, on the other hand, from the decreasing points only was 3.6 times greater than that from the increasing points only. The effect of warping is thus much greater on the second degree term, as would be expected.

The final result for the change of length at a mean temperature of 24° is:

$$-\Delta l/l_0 = 1.942 \times 10^{-7}p - 0.23 \times 10^{-12}p^2,$$

and for the change of volume:

$$-\Delta V/V_0 = 5.826 \times 10^{-7}p - 0.80 \times 10^{-12}p^2.$$

Using only the three smoothest of the many runs and simple graphical methods of calculation, a linear term of 1.939 was found against 1.942, and for the second degree term 0.34 against 0.23. Or if all the measured points had been retained, making no discards, it was apparent without making the calculations that the result would not have been much different; the average compression to 30,000 would have been 0.3 per cent greater.

The result found now is to be compared with my former value[3] up to 12,000 at 24°, namely:

$$-\Delta l/l_0 = 1.953 \times 10^{-7}p - 0.75 \times 10^{-12}p^2$$

The linear terms do not differ greatly, but the second degree term now appears to have been formerly much too large. This is the direction in which the theoretical physicists have been insisting was probable. It is also in the direction demanded by the measurements of Ebert[4] on an iron single crystal in the pressure range up to 5,000 kg/cm²; his second degree term is -0.4×10^{-12}. Exact comparison of my former and present results is hardly possible, because of the difference of range and because there can be only a heuristic significance in the second degree expression used to represent the results. It would be hopelessly beyond the accuracy of either former or present measurements to search for any real departure from the second degree relation.

The most natural point to seize on in attempting to explain the difference between the second degree term found now and formerly is that now the second degree term in the manganin gauge is taken into consideration, whereas formerly a linear relation was used. The deviation from linearity found for the present manganin gauge is in the abnormal direction, the resistance increasing with pressure at a decreasing rate at the higher pressures. The result is that a linear extrapolation from the low pressure readings gives too low a pressure at the high pressures. Hence as far as the present gauge is concerned the linear compression of iron would have been found more linear than it is if a linear calibration had been used for the manganin. However the effect is small: at 30,000 the true pressure is 1.3 per cent greater than would have been obtained from a linear extrapolation of the manganin gauge from 15,000. Using a linear relation for the manganin would have given a second degree term in the compression of iron only one third that given above, which is in the wrong direction to explain the discrepancy. The situation, however, is by no means simple, and it is not possible to argue back with certainty from these results to the previous source of difference. The second degree term in the manganin has to be found by individual calibration of each coil, and differs appreciably for contiguous pieces from the same spool. The manganin used in the previous work was from an entirely different source from the present manganin. If the former manganin had a small second degree term of the normal sign the former larger value of the second degree term in the compression of iron would be accounted for. The possibility cannot be ruled out that the curvature of the relation between the resistance of manganin and pressure reverses on passing from a low pressure range to one more extensive. It must furthermore be remembered that because of the difference of range the accuracy of the second degree terms in the present work is, other things being equal, more than six times that of the previous work.

It was my original hope to also measure the temperature coefficient of compression with this apparatus. In view, however, of the difficulties encountered in the measurements under the comparatively favorable conditions at room temperature it seemed hardly practical to try for the temperature effect. The best that can be done at present is to use the former value for the temperature coefficient. This would give at 75°:

$$-\Delta l/l_0 = 1.964 \times 10^{-7}p - 0.23 \times 10^{-12}p^2.$$

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THE COMPRESSION OF 46 SUBSTANCES TO 50,000 kg/cm^2

By P. W. Bridgman

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Introduction

Values for the compression of several substances up to 45,000 kg/cm^2 at room temperature have already been published.[1] In the following the method has been considerably improved and measurements made of the compression of 39 compounds which crystallize in the cubic system and whose structural constants are known from X-ray analysis, together with a few other substances, in the range up to 50,000 kg/cm^2, and at two temperatures, room temperature and − 78.8°, the subliming temperature of solid CO_2 at atmospheric pressure.

Method and Apparatus

In brief the method is differential. The material to be measured is surrounded by a plastic solid to transmit pressure approximately hydrostatically, and then compressed in a properly reinforced vessel by the motion of a piston. The displacement of the piston is measured as a function of pressure. Distortion of the vessel and other parts is eliminated by making the method differential, that is, by determining with a similar set-up the piston motion required to compress a very much less compressible substance whose compression may be assumed known with sufficient accuracy from previous measurements in a smaller pressure range. The difference of the two piston displacements gives the differential compression, the distortion cancelling out if it can be assumed to be the same in the two set-ups. The accuracy of the method evidently decreases rapidly as the compressibility of the substance becomes smaller.

The chief improvement in the new apparatus consists in the more effective external support given the pressure vessel. Whereas the maximum external pressure on the vessel was formerly somewhat less that 17,000 kg/cm^2, in the new design it is 26,000. This more effective external support not only decreases the distortion of the vessel and so increases the accuracy of the results, since the corrections for distortion are somewhat uncertain, but also has the important effect of materially increasing the life of the vessel. Formerly, the vessel rarely survived twenty applications of the maximum pressure, whereas now survival of 70 or more applications is not uncommon.

It would not have been possible with the previous arrangement to have applied 26,000 to the outside of the pressure vessel, for so high a pressure is considerably beyond the strength of the heavy tapered collar by which the external pressure is exerted. To reach 26,000 it is necessary to give the collar itself external support; this was done by making the collar double, the inner collar being tapered and supported externally by being thrust into an outer collar. That is, there are now three stages in reaching the maximum pressure, instead of two as formerly. The inner collar and the outer collar now function in the same way as the pressure vessel and its collar functioned in the previous apparatus. In the new apparatus the external pressure is controlled independently of the internal pressure by means of a second hydraulic press, instead of producing the external pressure automatically by the same press that produces the internal pressure. This arrangement of the two presses was adopted in the first instance as a matter of convenience and in spite of its greater complication, because of the greater resulting flexibility, allowing a greater range of choice in the angles of the pressure vessel and collar and in the ratio of internal to external pressure. In the end, however, it proved necessary, because with the angles needed to reach the proper pressure automatically with a single press the strength of the pressure vessel against extrusion would have been too low.

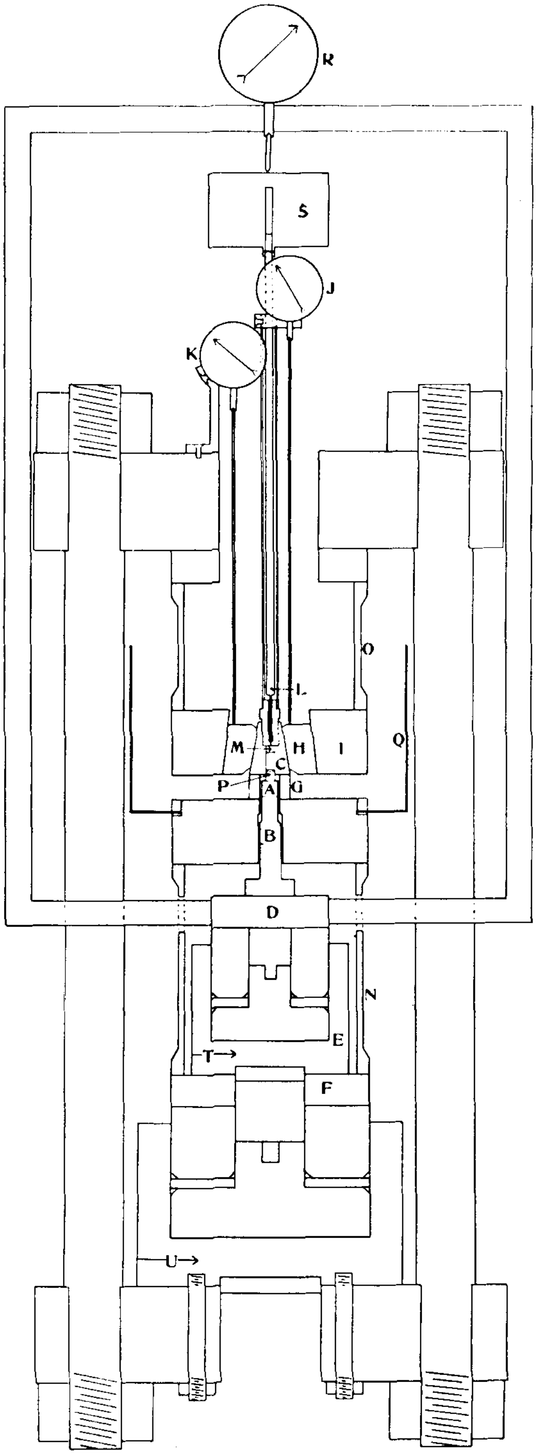

Figure 1. General view of the apparatus.

The new arrangement is shown in Figure 1, in which the parts are given to scale. The piston, P, with which the high pressure is produced, is of carboloy, from 0.250 to 0.262 inches in diameter, driven by a piston D 3.5 inches in diameter operated by a hand pump, the connection to which is indicated by the arrow T. The piston P rests on a carboloy block A 0.5 inch in diameter, which in turn rests on a hardened steel column B. The compressive stress in B is therefore only one quarter that in P, so that even with a pressure of 60,000 kg/cm^2 in P the steel column remains within its elastic limit. The high pressure vessel C is thrust into the conical steel collar H, which in turn is thrust into the external collar I by means of the 6 inch piston F, which is also actuated by a hand pump, the connection to which is indicated by the arrow U. The 3.5 inch piston D together with its cylinder, E, rides on F. The exterior of the pressure vessel C was given a much larger taper than in the previous work, the taper now being 4 inches to the foot (on the diameter) against 1.125 in the previous apparatus. At first a smaller taper was tried, but trouble was found from the pressure vessel tearing apart at the threads under the combined action of the force expelling the screw plug and the tendency of the vessel to extrude itself through the conical opening in H. This latter tendency is diminished by increasing the angle of the cone, allowing the walls to exert an increased longitudinal component in such a direction as to resist extrusion. The angle finally chosen was satisfactory in this regard, and the vessels very seldom fail at the threads. The chief disadvantage of making the angle of the cone large is that now a higher pressure must be exerted on the 6 inch piston F in order to generate a given pressure on the outside of C. With the dimensions given the pressure on F at the maximum was about 8,300 lb/in^2, which means a total thrust of 235,000 lb on the thrust ring G, which has a total area of a little less than one square inch. This thrust ring was made of "Solar" steel; the stress is near the elastic limit and the rings sometimes cracked from radial expansion, but after some trial the proper heat treatment was found. The taper on the outside of the inner collar H was 2.75 inches per foot. At the maximum the internal pressure on H was 26,300 kg/cm^2, and the external pressure 11,400 kg/cm^2. With the dimensions this was fairly near the elastic limit of the steel (Solar), and a couple of these rings broke in the preliminary work. The behavior of this ring is capricious; one was used for some 400 applications of the maximum pressure before breaking. The outer collar I is also of "Solar," specially forged on a mandrel to give circumferential working to the fibres. The internal pressure on it is the same as the external pressure on H, namely 11,400 kg/cm^2. It was given a preliminary treatment by a permanent stretching in two stages to a maximum of 17,500 kg/cm^2 internal pressure and then ground to final size. Three of these rings have fractured in use, all near the conclusion of the measurements. Since the fracture of this ring is accompanied by the explosive release of all the pressure on the 6 inch piston, the damage done may be considerable.

Lubrication at the sliding surfaces between C and H and between H and I was done much as before. There was in the first place a wrapping of 0.002 inch lead foil, which was smeared on both surfaces with a paste made of flake graphite and a 5 per cent soap solution. Formerly glycerine and water had been used in making this paste, but at CO_2 temperature this becomes very stiff and the friction high. Although the water in the soft soap freezes, the internal plastic flow strength of the ice is less than that of the congealed glycerine mixture, and the friction was very materially less. The internal mobility which is the accompaniment of the various polymorphic changes in the ice doubtless helps to reduce friction.

The displacements of C into H and of H into I were determined with two Ames gauges at J and K as part of the routine of the measurements. These displacements are not directly used in the final result, and need not be known with high accuracy, but they are a useful check on the proper functioning of all the parts. By plotting these displacements with rising and falling pressure the external friction on the cones may be found, and in this way a value for the external pressure, which enters the calculation for the distortion of the vessel. In general, the friction was reproducible to an unexpectedly high degree, so that no appreciable variation from run to run in the distortion correction arises from this cause. Because of the blunter taper of the cones the friction was much less than with the previous apparatus.

The crucial measurement is the displacement of P into C. Any attempted direct measurement of this is going to be somewhat in error because of distortion of various parts of the apparatus. A good deal of preliminary work was put into finding the best point of attachment for the gauge with which this displacement is measured. At some of the more obvious points of attachment the distortion may be so great as to more than mask the effect sought, giving under some conditions retrograde readings. The requirements in the point of attachment are that it be such that the distortion be reproducible, that it be free from frictional effects, and if possible that it be small. The arrangement shown in the diagram was checked by a variety of preliminary tests which it is not necessary to describe in detail, and seems entirely satisfactory. The most important feature of the final arrangement is the use of the fine hardened steel probe rod, L, reaching through the screw plug with which the pressure vessel is closed at the bottom, resting on a carboloy closing plug M. The longitudinal distortion of the threads of the closure plug could not be made reproducible, so that many simpler schemes could not be used. The block M must be of carboloy; hardened steel in this place is compressed beyond its elastic limit and the results are not reproducible. Various blank runs showed that the total distortion of the parts of the measuring system at the maximum pressure is 0.016 inch. All the parts are well under their elastic limits, and there was never any evidence to suggest that this distortion was not reproducible to the limits of error, so that it drops out from the final difference. The gauge with which the displacement of the piston is measured via the probe rod is an Ames dial gauge, R, graduated to 0.0001 inch and read to 0.00001 inch. In the previous work the displacement was read with a gauge only one tenth as sensitive, but a lever magnifying arrangement was interposed with a magnification factor of 3. There is outstanding therefore a factor of about 3 in favor of the new apparatus.

The order of magnitudes of the piston displacements was as follows. In a calibrating run in which the vessel was filled with iron and indium the total measured displacement at 50,000 was about 0.065 inch. Of this, 0.016 was contributed by the distortion in the press, 0.011 by the actual compression of the iron, 0.022 by the compression of the indium, and the balance 0.016 by the increase of cross section of the pressure vessel. The total measured displacement of the piston for a filling with a substance of average compressibility was 0.100 inch. The difference, 0.035, was therefore given to one part in 3500, reading the Ames gauge to its limit of sensitiveness. In spite of the smallness of the displacements, the accuracy was not limited by this factor.

In order to protect the Ames gauge from explosions, the probe rod transmits its motion through a brass pin and a heavy weight, S, the brass pin shearing off if the probe rod is explosively expelled. There is a further safety arrangement, not shown in Figure 1, which limits the motion of the screw plug, if it should be expelled in an explosion, to about 0.5 inch.

The thrust of the 6 inch piston is transmitted to the pressure vessel and from the collars supporting the pressure vessel to the frame of the press by means of the thin sleeves N and O of hardened tool steel. These are made of as small cross section as is safe to keep them certainly below the elastic limit. This is done in order that heat conduction from the bath in which the pressure vessel and its collars may be immersed may be as small as possible. In this work the can of sheet iron Q was filled with solid CO_2 and alcohol for the low temperature runs, and it was of course desirable to restrict thermal conduction to other parts of the apparatus as much as possible.

The essential measurement, beside the displacement of the piston into the pressure vessel, is the pressure on the piston P. This was obtained directly from the pressure in the liquid driving the piston D. It is therefore necessary that D move with the least possible friction. The interior of the cylinder E in which D moves was finished as smooth as possible by grinding, and the packing on the end of D was a smoothly cut disc of "Duprene" 0.125 inch thick held between retaining discs of brass also 0.125 inch thick. The friction with this arrangement is only a few per cent, and smaller than the friction on the high pressure end of the piston P. Simultaneously with the increase of internal pressure produced by increasing pressure on D, the external pressure on the vessel C must be increased by increasing the pressure on F. The internal volume of C is affected very materially by the changes of external pressure, so that if pressure on F is not increased smoothly, and in the correct ratio to the increase of pressure on D, the resulting displacements will be irregular. At first various schemes of manual control of the pressure on the two pistons D and F were tried without sufficient success. Finally D and F were connected by a pressure multiplier, not shown in Figure 1, so that the pressures on D and F were maintained automatically in the correct proportion, which was found by a preliminary trial. This pressure multiplier consisted simply of one piston pushing another of different area. There was, of course, some friction in the multiplier, but by using the same packing technique as on D (and F) this was kept to a sufficiently low figure. The capacity of the two cylinders of the multiplier was sufficient so that it was possible to reach the maximum pressure by pumping only into the side of the multiplier connected to F; similarly pressure was released by opening a valve in the F side of the multiplier.

The pressure on D was controlled by a 0.25 inch dead weight free piston gauge connected in series between the multiplier and D. Pressure was increased in 30 equal steps from zero to the maximum by succeessive addition of equal weights to the piston gauge, and similarly released by successive removal of weights. The procedure, after one reading was completed, was to place the next weight on the piston gauge, and then to pump by hand into F until the free piston gauge rose because of the increased pressure transmitted to it from the multiplier. The pipe connecting the piston gauge to D was constricted by a wire nearly filling the bore, so that pressure was transmitted only slowly from the piston gauge to D. In this way fluctuations in pressure were retarded and smoothed out so that pressure on D did not overshoot the mark while the piston gauge was overcoming the inertia of the weights and rising.

In spite of the external support, the pressure vessel is strained beyond the elastic limit at every application of pressure, and eventually breaks, although this may be deferred for 70 to 80 applications. The distortion of the vessel therefore shows hysteresis and all the other phenomena to be expected beyond the range of elasticity. In order to obtain reproducible results it is necessary to proceed on a rigorous time schedule. At each temperature, room temperature or carbon dioxide temperature, a seasoning application of the maximum pressure was first made in six large pressure steps, and readings made with increasing and decreasing pressure to check that the apparatus was functioning properly and roughly to locate any polymorphic transitions, if there were such. The regular readings were then made in 30 equal steps up and 30 equal steps down on a time schedule of 2 minutes to the step, the gauge R being read on the conclusions of the 2 minutes and immediately before the next increase of pressure, the pressure in the meantime having been held constant by the piston gauge. Piston displacements (readings of R) were then plotted against pressure. The result is a loop, the decreasing readings never coinciding with the increasing readings because of friction in one place or another and because of hysteresis in the distortion of the pressure vessel. The greatest friction is at the end of the piston P and in the material in the interior of the pressure vessel as it slides along the walls to take up the compression. As in the measurements already published, the material under measurement is enclosed in the pressure vessel in a capsule of a soft metal, by which pressure is transmitted to it approximately hydrostatically. In the previous work this metal was lead. Preliminary exploration before these measurements showed that indium is somewhat superior to lead for this purpose, being materially softer, and it was accordingly used in all this work. The amount of indium required is small, and it can be used a number of times, so that the expense was not an important factor.

The total width of the loops of piston displacement against pressure, that is the difference between increasing and decreasing pressure for a fixed displacement, averaged about 12 per cent of the mean pressure at the maximum. The error in the curve median to the loop cannot therefore possibly be more than 6 per cent. The actual error in the median curve of course is much less than this, since it is determined by the failure of friction and hysteresis to be reproducible on the different runs. This 6 per cent is the net result of all the differences between the ascending and the descending branches. Friction at the various pistons produces a true *hysteresis* loop, the displacement with decreasing pressure lagging behind that with increasing. Paradoxically, however, friction on the external conical surface of the pressure vessel makes a contribution to the loop in which the displacement *leads* instead of lags, because when pressure is too high on the exterior of the vessel the internal volume is too small and the piston has to be withdrawn to compensate. This effect may be very appreciable, and it was not at all unusual for the loop at CO_2 temperature to be narrower than at room temperature because of the greater friction on the conical surface between C and H. It follows that the narrowness of the loop cannot be used as an exclusive criterion for the satisfactory functioning of the apparatus, but this has to be combined with an examination of the friction at the various surfaces, which may be determined from the readings of J and K.

In the previous work the median curve through the hysteresis loop was obtained by plotting against pressure the mean of the displacements with increasing and decreasing pressure. Since increasing and decreasing measurements were made at exactly the same pressures, this sort of average was very easy to obtain by calculation. However, a discussion of the way in which friction inside the high pressure vessel affects the mean compression showed that the other sort of averaging, that is, the mean of increasing and decreasing pressure at constant displacement, was preferable. Although this sort of averaging is considerably more inconvenient to apply, it was adopted in the following. The difference between the two methods of averaging is quite appreciable for some substances, and the superiority of this method of averaging was checked by the fact that the agreement between repetitions with the same substance was improved. The new method of averaging was applied graphically. The observed points were plotted on millimeter paper to a scale of about 30 centimeters range in abscissae to 40 centimeters range in ordinates, a smooth curve was drawn through ascending and descending points (60 points in all) with a "ship's" curve, then the loop was bisected at some 20 uniformly spaced displacement points with a simply constructed special drawing instrument for bisecting lines, and finally a smooth curve was again drawn through the mean points. The end of the loop at the maximum pressure, where the direction of pressure change is reversed, required special treatment. Obviously on reversal there is back lash in the various parts, so that the loop is closed with a rounded end in the familiar way. When pressure is reduced so far that backlash in all the parts has disappeared the ascending and descending branches differ by the whole frictional effect, which is approximately proportional to the pressure. The difference between the two branches of the loop should therefore be proportional to the pressure over most of the range. This did indeed prove to be the case, showing incidentally that hysteresis in the pressure vessel makes only a small contribution. The constant of proportionality was determined graphically from the loop itself, and the descending branch was extended by calculation by means of this constant, as shown by the dotted line in Figure 2, and this dotted curve was used in getting the mean at the upper end of the loop. Backlash on reversal ceased to be perceptible when pressure had been released by something of the order of 20 per cent of the maximum. Because of friction it was necessary to run the maximum pressure on the piston to about 53,000 kg/cm^2 in order that the mean maximum pressure on the inside should be 50,000.

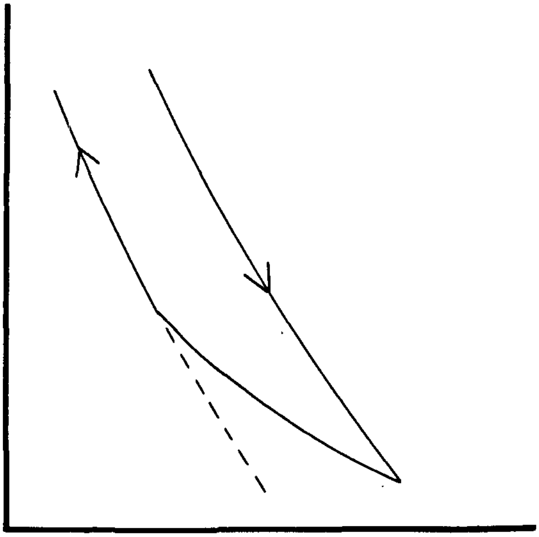

FIGURE 2. The upper end of the hysteresis loop, and the method of extending the reverse branch to eliminate the effect of backlash. Ordinates are piston displacement and abscissas pressure.

Considerable preliminary work was put into finding the steel most suitable for the pressure vessel. The steel finally chosen was the "Omega" steel of the Bethlehem Steel Corporation. A typical analysis is: C, 0.55; Mn, 0.80; Si, 2.30; V, 0.25; Mo, 0.50; P, 0.015; S, 0.025. This is an oil hardening steel, and is somewhat less capricious in its behavior than "Solar," the water hardening steel used previously, and which is still used in other parts of the apparatus. The vessels were heat treated by quenching into oil from 885° C. and drawing back to a Rockwell C. hardness of 56–57. It is still possible to force a high speed steel reamer through the hole at this hardness if only a few thousandths of an inch is removed. The vessels were first made to 0.250 inch in diameter, and then subjected to a preliminary stretching to a maximum pressure of about 56,000. During this stretching the ratio of the pistons of the multiplier had to be changed to get the correct external pressure. This preliminary stretching was done in two steps: the first with the whole vessel filled with indium to stretch the body of the vessel, and the second with much of the indium replaced with a core of iron, to stretch the mouth of the hole. Under this preliminary stretching the bore increases to something of the order of 0.257 inches. It was then reamed to 0.260 inches and was ready for use. The first stage in use consists of a blank calibrating run in which approximately the same amount of indium is used as is to be used in the later measuring runs, and in which a core of iron of approximately the volume of the substance to be measured later replaces it. Unfortunately the different vessels, in spite of every effort, differed so much that such calibrating runs proved necessary for each individual vessel. The blank calibrating run demands the application of the maximum pressure four times: one seasoning and one regular at each temperature. The vessel is now ready for regular measurement with any substance. Again four applications of the maximum pressure are necessary. The vessel does not begin to give results therefore until it has withstood the application of the maximum eight times, not counting the preliminary stretching. In the previous work the vessel broke frequently before reaching eight applications, so that this was a most discouraging requirement, and in fact was not enforced. But the accuracy is much improved by it. After every set-up the bore of the vessel was freshly measured. In spite of the preliminary stretching it continues to slowly stretch. The current value of the diameter was of course used in the calculations. When it gets to as much as 0.263 inches the vessel is discarded, if it has not already broken. As already mentioned, vessels have been used for 70 to 80 applications (20 fillings). It is to be anticipated that the calibration will slowly change as the vessel stretches. For this reason the routine procedure was adopted of making a fresh blank calibration on every fifth set-up, thereby further improving the accuracy. As a matter of fact the successive calibrations were gratifyingly reproducible after due allowance was made for the slight stretch. As calibrations accumulated a mean of the calibrations was used in the calculations.

The experiments were usually limited by two sorts of rupture, rupture of the pressure vessel and of the carboloy piston. Other places where rupture might be expected to occur are in the tapered supporting collars and in the tool steel sleeves supporting the temperature bath. The latter never ruptured, but in the initial design they were a little too thin, so that they took a permanent set of a few thousandths of an inch. This might be serious, because it is evident that the alignment of all the parts must be good if the carboloy piston is to receive an entirely straight thrust, which is essential. The sleeves were remade about 25 per cent thicker and have never given any further trouble except during one major explosion of another part. The present dimensions are a wall thickness of 0.187 inch and 6 inches diameter. The tapered collars have also given comparatively little trouble; three ruptures of the outer collar have occurred and three of the inner. The carboloy pistons, however, are another story. These are likely to break at any time, and a constant watch must be kept after every run for the appearance of fine longitudinal cracks, which are the prelude to complete failure, and the piston must be at once discarded. Final rupture of a piston may be a most violent affair, when it is often reduced to a fine powder. Such rupture occurs so rapidly that the multiplier has no time to function, with the result that the pressure vessel is exposed to the full external pressure with no compensating internal pressure. The result is that the vessel is appreciably collapsed, and has to be discarded. The strains set up in the vessel by this collapse are so severe that often the vessel spontaneously ruptures hours or perhaps days after the explosion. Loss of the pressure vessel means not only loss of the particular run but also loss of all the labor of calibration. After a few unfortunate occurrences of this kind, subsequent occurrences have, to a large extent, been prevented by keeping a most careful watch for the first appearance of fine cracks in the piston. Fracture of the piston was often initiated in the early work by slight chipping around the edges. This can be largely avoided and the life of the piston much prolonged by forcing the thin supporting disc of hardened alloy steel shown in Figure 3 around the end of the piston. The other end of the piston which enters the pressure vessel is adequately supported by the walls of the vessel, and chipping practically never occurs at this end. The carboloy piston is pushed by a carboloy block 0.5 inch in diameter, against which it directly rests, both surfaces being ground flat. This block has ruptured oftener than would be anticipated because of its dimensions, and a careful watch must be kept for the development of cracks.

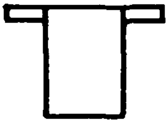

FIGURE 3. Reinforcement of the carboloy piston with a thin disc of heat treated alloy steel.

In spite of every endeavor both by myself and by the manufacturers, the performance of the pistons remains capricious, and the life may vary from 2 or 3 to more than 100 applications of the maximum. Attempts were made to correlate the life with the density and with Young's modulus. I am much indebted to Dr. Dennison Bancroft for measurements by his dynamic method of Young's modulus of a number of rods from which the pistons were cut. Probably there is some correlation with both density and modulus, long life

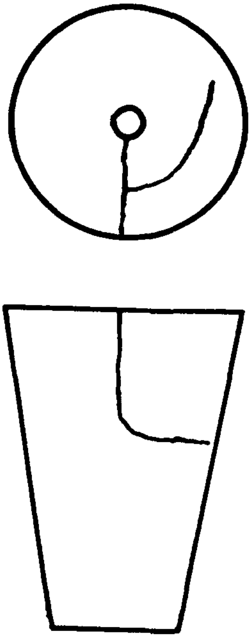

FIGURE 4. Two views of the pressure vessel with a system of three mutually perpendicular fractures.

having a tendency to go with high density and high modulus, but the correlation is not close enough to be a useful practical guide. One thing is certain, however. In cutting the pistons to length and in facing the ends the use of diamond charged wheels is necessary. The cutting must be free and without forcing; otherwise there is local heating and strains are set up which may initiate rupture of the whole piece.

The method of rupture of the vessels is capricious; apparently the limit of strength in all possible directions is reached nearly simultaneously. The same vessel may show radial and circumferential rupture and also rupture perpendicular to the longitudinal axis, as suggested in Figure 4. The rupture is practically always an extension rupture; I do not remember ever having seen a shearing rupture. It is quite common for the crack to develop after the vessel has been standing for some time free from any external force.

Method of Calculation and Corrections

The following simplified equations were used in calculating the results. Imagine runs with two different set-ups; in each set-up the vessel is filled with two different substances, the amounts of which differ for the two set-ups.

Let M and M' be the masses of the first substance (presumably indium) for the two set-ups respectively.

Let m and m' be the masses of the second substance (presumably iron) for the two set-ups respectively.

Let l_o and l_o' be the initial lengths of the pressure vessel for the two set-ups respectively.

Let l_p and l_p' be the lengths of the pressure vessel at pressure p for the two set-ups respectively.

Let s_o be the initial cross section of the pressure vessel.

Let $s_p = s_o\ (1 + \Delta)$ be the cross section of the pressure vessel at pressure p.

Let V_o and V_p be the volumes of one gram of the first substance initially and at pressure p respectively.

Let v_o and v_p be the volumes of one gram of the second substance initially and at pressure p respectively.

Then we have the equations:

$$\begin{aligned} MV_o + mv_o &= l_o s_o \\ MV_p + mv_p &= l_p s_p \\ &= l_p s_o\,(1 + \Delta) \end{aligned}$$

$$\begin{aligned} M'V_o + m'v_o &= l_o' s_o \\ M'V_p + m'v_p &= l_p' s_p \\ &= l_p' s_o\,(1 + \Delta) \end{aligned} \qquad (1)$$

There are essentially three unknowns here, V_p, v_p, and Δ, and two equations, the first equations for each set-up being merely check equations. It is not possible to provide a third equation from which these three quantities may be determined by making a third set-up with different relative quantities of the two substances, for the equations obtained in this way are only identities, useful only for check. By eliminating V_p between the last two equations above one gets:

$$1 + \Delta = \frac{v_p[mM' - m'M]}{s_o[M'l_p - Ml_p']} \qquad (2)$$

Hence if v_p, the volume of the second substance, which in this experiment was pure iron, is known as a function of pressure, the distortion of the cross section can be obtained in terms of measurable quantities. I have recently determined v_p by direct measurement[2] up to 30,000 kg/cm^2. The deviation from linearity is so slight that there can be no hesitation about extrapolating to 50,000. In fact the final value for the cross section that one obtains by extrapolating the new experimental measurements of the volume of iron from 30,000 to 50,000 differs by less than 0.1 per cent from the value obtained by an extrapolation to 50,000 of the former measurements of compressibility to only 12,000.

It is also possible to calculate Δ by the methods of conventional elasticity theory. This method was used in the previous paper,[3] to which reference is made for the details of the calculation. The value calculated in this way for Δ at 50,000, by assuming the conditions of an infinitely long cylinder, was 0.026, whereas the experimental value was 0.0271. The agreement is most gratifying. The value 0.0271 was used in all the reductions of this paper for the value at 50,000. For intermediate pressures it was assumed linear with pressure; the variation with temperature was neglected.

The quantity l_p' which enters equation (2) above is not given directly by the measurements, nor is it determinable directly from l_o' and the measured displacement of the piston, for the latter involves the distortion of various parts of the press. These distortions were determined by various secondary measurements, as already indicated, but which need not be described in greater detail.

However, once the correction for distortion of the cross section has been determined, the corrections for the distortion of the press need no longer enter, but drop out by taking differences of the measured displacements. By thus taking differences in pairs of the equations (1) above one has:

$$M\,(V_o - V_p) + m\,(v_o - v_p) = s_o\,(l_o - l_p) - s_o l_p\,\Delta$$
$$M'\,(V_o - V_p) + m'\,(v_o - v_p) = s_o\,(l_o' - l_p') - s_o l_p'\,\Delta \tag{3}$$

But

$$l_o - l_p = (\mathit{Observed\ Displacement})_p - (\mathit{Correction\ for\ press\ distortion})$$
$$l_o' - l_p' = (\mathit{Observed\ Displacement})_p' - (\mathit{Correction\ for\ press\ distortion})$$

Subtracting,

$$-l_p + l_p' = (\mathit{Observed\ Displacement})_p - (\mathit{Observed\ Displacement})_p' + l_o' - l_o$$

Subtracting the two equations (3) above and substituting

$$(M - M')\,(V_o - V_p) + (m - m')\,(v_o - v_p) = s_o \{(1 + \Delta)[(\mathit{Obs\ Dis})_p - (\mathit{Obs\ Dis})_p'] + \Delta(l_o' - l_p)\} \tag{4}$$

This equation gives the compression of the first substance in terms of the assumed compression of the second substance, the correction for the cross section, the difference of observed displacements in the two runs, and other quantities obtainable from measurements at atmospheric pressure. The compressibility of indium was determined in this way.

The volume of indium having been thus determined as a function of pressure by a number of preliminary measurements, the regular program of compressibility determinations could be begun. This comprised in the first place a blank run, in which the vessel was filled with indium and iron, and a second run in which the iron was replaced by an approximately equal amount of the material to be measured, and an amount of indium roughly equal to that of the calibrating run. The relations can be described in equations similar to those already written. If M_1 refers to the first run and M_2 to the second, and the subscripts *In*, *Fe*, and x to indium, iron, and the substance to be measured respectively, then one has the equation:

$$M_2\,(v_{ox} - v_{px}) = s_o\,\{(1 + \Delta)[(\mathit{Obs\ Dis})_{2,p} - (\mathit{Obs\ Dis})_{1,p}] + \Delta\,(l_{o1} - l_{o2})\} + (M_{2Fe} - M_{1Fe})(\Delta v)_{p.Fe} + (M_{2In} - M_{1In})(\Delta v)_{p.In} \tag{5}$$

The term M_{2Fe} does not vanish, as one might perhaps at first expect, because a certain amount of steel always had to be used in the various packing rings. These rings were weighed and kept as constant in magnitude as feasible; no appreciable error is to be expected from their slight variation. The compressibility of the alloy steel of which the packing rings were made was assumed to be the same as that of pure iron; measurements up to 12,000 already made justify this assumption. It is to be noticed that the compression of the indium enters the final result only as a correction, the endeavor being to make M_{2In} equal to M_{1In}.

The equations written above have the appearance of rigor; there are, nevertheless, a number of tacit assumptions. The interior of the pressure vessel is not actually deformed into a cylinder with constant cross section $s_o(1 + \Delta)$, but it must be somewhat barrel shape. Δ refers to the average cross section. If the vessel were infinitely long the end effects could be neglected. The value of Δ calculated above by elasticity theory assumes an infinitely long cylinder. The end corrections vary somewhat from run to run with the different amount of filling and different amount of compression. The difference between such end effects is neglected above. The most important part played by the end effect is in determining the effective cross section on which the piston acts to produce pressure. As already stated in the previous paper, Betti's reciprocal theorem shows that in an infinitely long cylinder the distortion of the cross section at the moving piston is only one half the full value reached at some distance from the piston. Hence in calculating the pressure from the total thrust on the piston, the cross section was corrected by only one half the amount given above, namely by 1.35 per cent at 50,000. This correction for the cross section at the piston obviously enters in turn into the calculations by which Δ was found; the method was one of successive approximations in which the convergence was so rapid that only two steps were necessary.

The relative importance of the corrections in the final result arising from the compression of the iron and the indium varies with the material and the particular set-up. The correction for iron is relatively less for the more highly compressible substances. The correction for indium depends on the accidents of the filling, being small when the quantity of indium in the measuring run was nearly equal to that in the calibrating run. The most incompressible substance measured in the following was ZnS; here the correction for iron was nearly one half the total final value and the correction for indium was 3 per cent of the final value. The most compressible substance was CsI; here the correction for iron was 11 per cent of the final value and that for indium 1.6 per cent. The correction for indium rarely exceeded the values just given. The error in the final result of course depends on the error in these corrections, which is thus small.

The error in the final result is unfortunately not limited by all the factors just discussed, which would be so small that they could be regarded with complacency. By far the most important source of error is irregularity in the distortion of the pressure vessel, which is connected with the magnitude of the strains, departure from linearity, hysteresis, and friction. There seems to be no way of estimating this error except by the consistency of the results. Every substance was accordingly measured twice, and some of them more times, with different vessels. The average of the two set-ups was usually taken. It is a fortunate feature of this situation that error from this sort of irregularity should be as often positive as negative. Theoretically one could reduce indefinitely the error by making many set-ups. As is to be expected, the discrepancies between different set-ups are usually greater for the more incompressible substances. As already mentioned, the most incompressible substance attempted in the following was ZnS (sphalerite). Its compression at 50,000 is about 5 per cent; this is smaller than could in general be profitably attacked by this method. CsI on the other hand has a compression of about 20 per cent. As a rough average for all substances, the total compressions to 50,000 should be accurate to better than 5 per cent of themselves.

At the low pressures the method is insensitive; in some cases other data have been incorporated into the low pressure values. All the values given in the following have been smoothed and have been tabulated at 5,000 kg intervals. In the smoothing process only the results for that particular set-up and the particular temperature were considered. No attempt was made to adjust the values so as to give what might be conceived to be more probable variations with temperature, or so as to give a more regular progression of results from member to member of a chemical series of substances. The number of figures retained in the final results is governed by considerations of smoothness rather than of absolute accuracy. In the smoothing the measured value of the compression between zero and 5,000 was given little weight, and the tabulated values were almost always obtained by smooth graphical extrapolation downward of the values at higher pressures. It may very well be that transitions of the second kind or even very small first order transitions, have been wiped out by the smoothing process; occasional possibilities of this sort are mentioned in the following. In general, such transitions must wait for more accurate methods, such as that now being developed up to 30,000.

All measurements were made at room temperature and carbon dioxide temperature. The inconsistencies of the low temperature readings were materially greater than of the readings at room temperature, so that the temperature coefficients of compression for any one substance cannot be regarded as very accurate. The general picture of the behavior of the temperature coefficient presented by all the substances should be essentially correct, however, and I believe that the extra labor of making measurements at the lower temperature was probably justified. Again the probable accuracy of the temperature coefficient could be indefinitely increased in any crucial case by sufficiently multiplying measurements.

DETAILED PRESENTATION OF DATA

The order of presentation is: first indium, because its compression is used as a correction in all the measurements; then the monovalent chlorides, bromides, and iodides of sodium, potassium, rubidium, caesium, ammonium, silver, and thallium; then the divalent sulfides, selenides, and tellurides of calcium, strontium, barium, lead, zinc, and mercury; then some of the more compressible elements; and finally rubber, measured only incidentally and in a single variety, to assist in the design of the packings.

The measurements were always made on weighed quantities of the materials. In order to convert these into compressions or fractional changes of volume, it is necessary to know the density. In the following the compressions are given as the volume decrement in cm^3 of a number of grams equal to the density. The results are given in this way so that if at some future time better values are found for the density a simple multiplicative correction can be applied. Most of the densities used in the following are X-ray densities, based on the lattice constants given in Wyckoff's book *The Structure of Crystals*.

Indium. Measurements of this were made with five different set-ups in five different vessels; of these only three were at both temperatures, the other two being only at room temperature. The material was obtained from MacKay, of 99.9 per cent purity or better. In the table the value 7.31[4] for the density was used; in computing the corrections the exact value is immaterial, since it cancels out.

At room temperature the extreme values for the compression at 50,000 of 7.31 grams were 0.0851 and 0.894; at CO_2 temperature the extreme values were 0.0870 and 0.0899. The extreme values at the two temperatures were not consistently given by the same vessels. Two of the three determinations of the temperature coefficient of compression agreed in giving an abnormal negative value at high pressures; the third was positive but smaller than the other two. In the calculations the resultant negative coefficient obtained by averaging was used. Even if one is not convinced that this represents the actual behavior of indium, nevertheless it does represent the apparent behavior in the apparatus, and so should be used in subtracting from the results for other substances. The correction is in any event so small that it can hardly be an appreciable factor in the final results for the temperature coefficients of the other substances.

The unweighted arithmetical average of the different set-ups is given in Table I. Rough values for the compression of indium at room temperature have already been published.[5] The agreement is within 2 in the second significant figure up to 25,000, but beyond this the divergence increases, the former value at the former maximum pressure, 45,000, being 0.091 against 0.081 now found. That is, the decrease of compressibility with increasing pressure is now greater than before.

TABLE I

COMPRESSION OF INDIUM

Pressure kg/cm^2	ΔV cm^3/7.31 gm	
	R. T.	CO_2 T.
5,000	.0116	.0114
10,000	.0224	.0222
15,000	.0328	.0328
20,000	.0425	.0427
25,000	.0518	.0520
30,000	.0600	.0607
35,000	.0678	.0686
40,000	.0749	.0759
45,000	.0813	.0825
50,000	.0870	.0885

NaCl. The material was natural clear halite crystal. Four different set-ups were made with four different vessels. Of these four gave readings at room temperature and two at CO_2 temperature. The extreme values of the compressions at 50,000 were 0.1240 and 0.1346 at room temperature and 0.1254 and 0.1321 at CO_2 temperature. The averages are given in Table II. The compressions at the lower temperature were adjusted to compensate for the fact that there were four runs at room temperature and only two at CO_2 temperature. The temperature coefficient of compression was obtained by comparing the average of the same two set-ups at the two temperatures. This difference was then applied to the average of the four runs at room temperature to give the compressions at the lower temperature.

TABLE II

COMPRESSIONS OF THE SODIUM HALIDES

Pressure kg/cm^2	NaCl cm^3/2.163 gm		NaBr cm^3/3.205 gm		NaI cm^3/3.667 gm	
	R. T.	CO_2 T.	R. T.	CO_2 T.	R. T.	CO_2 T.
5,000	.0192	.0177	.0228	.0216	.0296	.0290
10,000	.0365	.0341	.0430	.0413	.0553	.0547
15,000	.0523	.0494	.0610	.0594	.0778	.0772
20,000	.0664	.0634	.0771	.0756	.0974	.0966
25,000	.0798	.0763	.0916	.0904	.1145	.1139
30,000	.0919	.0880	.1047	.1037	.1294	.1288
35,000	.1029	.0987	.1166	.1157	.1424	.1421
40,000	.1130	.1084	.1274	.1263	.1538	.1538
45,000	.1223	.1172	.1373	.1357	.1638	.1642
50,000	.1309	.1250	.1464	.1439	.1728	.1738

Rough values for the compression to higher pressures have already been published.[6] At 45,000 at room temperature, the previous maximum, the former value was 0.118 against 0.127 found now. The difference is in the opposite direction from that for indium. There are also unpublished measurements of the linear compressibility up to 30,000 by the more accurate method to be described in another paper. These values are slightly lower than found here, at 30,000 being 0.0913 against 0.0919. Earlier determinations[7] of the compressibility to 12,000 gave for the changes of volume at 30° at 5,000 and 10,000 respectively 0.0197 and 0.0368 against 0.0192 and 0.0365 above.

NaBr. The material was from a perfectly clear single crystal prepared by my method of solidification from the melt. Three set-ups were made at room temperature and two at CO_2 temperature. The extreme compressions at room temperature at 50,000 were 0.1417 and 0.1488 and at the lower temperature 0.1417 and 0.1509. Up to 30,000 the extreme difference between different runs is only 1 in the third decimal place, but above 30,000 the runs begin to diverge more. The temperature coefficient of compression above 30,000 is doubtless less reliable than below 30,000. The averages are given in Table II. The compressions tabulated at the lower temperature were adjusted for the different number of set-ups at the two temperatures in the same way as already explained for NaCl.

The compressions up to 12,000 have been previously determined by Slater.[8] At 30° at 5,000 and 10,000 they were respectively 0.0234 and 0.0436 against 0.0228 and 0.0430 above.

NaI. The material again was clear single crystals solidified from the melt. Four set-ups were made at room temperature and two at CO_2 temperature. The extreme compressions at 50,000 at room temperature were 0.1661 and 0.1801, and at the lower temperature 0.1714 and 0.1756. The compressions at the lower temperature in the final results were adjusted as before for the different number of runs at the two temperatures. The averages are given in Table II.

The compressions up to 12,000 have been previously determined.[9] At 30° at 5,000 and 10,000 they were respectively 0.0301 and 0.0546 against 0.0296 and 0.0553 above.

KCl. The three potassium halides have a transition with large change of volume from the NaCl structure to presumably the CsCl structure in the neighborhood of 20,000, the parameters for which have been studied before.[10] The transition pressures and the changes of volume were now measured again in the natural course of the work. The pressure steps of this work were larger than would have been chosen if the transition were being studied for itself alone, so that for this reason the parameters would not be expected to be as accurate as before, but on the other hand, the effective region of indifference now appeared narrower than before, so that for this reason the results should now be more accurate. In any event this is the first time that transition measurements have been made at CO_2 temperature.

The KCl was clear single crystal material, crystallized from the melt. Three set-ups were made at room temperature and two at CO_2 temperature. The extreme compressions at room temperature at 50,000 were 0.2565 and 0.2603, and at CO_2 temperature 0.2466 and 0.2537. At room temperature the transition pressures varied from 19,840 to 20,290, and the fractional change of volume ($cm^3/1.988$ gm) from 0.1122 to 0.1143. At CO_2 temperature the corresponding figures were 20,200 to 20,990, and 0.1095 to 0.1145. The compressions tabulated at CO_2 temperature are adjusted in the regular way for the different number of runs at room temperature and CO_2 temperature. The averages are given in Table III. The new average transition pressure at room temperature is higher than found before, 20,060 against 19,900. If the transition line is linear, the slope now found has the opposite sign from that found earlier, but there is no assurance that the line is straight, and the whole question would have to be examined again with greater care over the entire temperature range to be sure of this point. The new change of volume at the transition is 0.1133 against 0.1094 formerly. The new value should be at least as good as the old.

TABLE III

Compressions of the Potassium Halides

Pressure kg/cm²	KCl $cm^3/1.988$ gm		KBr $cm^3/2.75$ gm		KI $cm^3/3.123$ gm	
	R. T.	CO_2T.	R. T.	CO_2T.	R. T.	CO_2T.
5,000	.0257	.0241	.0295	.0272	.0351	.0335
10,000	.0478	.0452	.0547	.0511	.0648	.0623
15,000	.0667	.0645	.0758	.0720	.0905	.0868
20,000	.0841	.0807	.1989	.1933	.1970	.1932
25,000	.2111	.2055	.2138	.2078	.2149	.2105
30,000	.2225	.2158	.2267	.2202	.2296	.2244
35,000	.2324	.2255	.2379	.2308	.2421	.2363
40,000	.2419	.2340	.2479	.2399	.2532	.2466
45,000	.2501	.2418	.2569	.2481	.2629	.2554
50,000	.2579	.2497	.2650	.2552	.2715	.2630
			Transitions			
Press.	20,060	20,590	18,430	19,400	18,200	19,010
Δv	0.1133	0.1120	0.1052	0.1044	0.0850	0.0872

The compression to 12,000 has been measured by Slater.[11] His values at 30° were 0.0258 and 0.0479 at 5,000 and 10,000 respectively against 0.0257 and 0.0478 above.

KBr. The material was clear single crystals, crystallized from the melt. Three set-ups were made at room temperature and two at CO_2 temperature. At room temperature the extreme compressions at 50,000 were 0.2618 and 0.2697, and at CO_2 temperature 0.2567 and 0.2570. At the latter temperature the agreement of the two runs was practically perfect over the entire pressure range. The averages are given in Table III. Adjustment is made at CO_2 temperature for the different number of runs at the two temperatures in the regular way.

At room temperature the range of transition pressures was from 18,400 to 18,470; the agreement is doubtless partly accidental. The range of the change of volume was from 0.1025 to 0.1079. At CO_2 temperature the transition pressure ranged from 19,380 to 19,420, and the change of volume from 0.1026 to 0.1060. At room temperature the transition pressure is now 18,430 against 19,300 found formerly, and the fractional change of volume is now 0.1052 against 0.102. I believe that the new values are better; the effective band of indifference is here only 7,800 kg/cm^2 wide against 13,600 before.

The compression up to 12,000 has been previously measured by Slater.[12] His values at 30° at 5,000 and 10,000 were 0.0302 and 0.0556 respectively against 0.0295 and 0.0547 above.

KI. The material was clear single crystals, prepared from the melt. Four set-ups were made at room temperature, and three at CO_2 temperature, since the variations were somewhat greater than usual. At room temperature the extreme compressions at 50,000 were 0.2620 and 0.2843; at CO_2 temperature the corresponding figures were 0.2576 and 0.2701. The transition pressures at room temperature ranged from 17,530 to 18,550, and the fractional changes of volume from 0.0825 to 0.0892. At CO_2 temperature the corresponding figures were 18,520 to 19,370 and 0.0847 to 0.0903.

The averages are given in Table III. Adjustment was made for the different number of runs at the two temperatures as usual. The average transition pressure at room temperature is now 18,200 against 17,850 formerly, and the fractional change of volume 0.0850 against 0.083 previously. The new figures are probably better; the new region of indifference is 8,900 kg/cm^2 wide against 13,400 previous.

The compression has been measured up to 12,000 previously by Slater.[13] His values at 30° at 5,000 and 10,000 were 0.0379 and 0.0678 respectively against 0.0351 and 0.0648 here. The agreement is not as good as for the other sodium and potassium salts.

If it is assumed that the transition lines for all three halides are straight over the entire temperature range, the new results agree in giving a negative value of $d\tau/dp$ to all three potassium halides, whereas formerly the signs for KCl and KI were positive and for KBr negative. The fractional changes of volume at the transition increase from iodide to bromide to chloride; this agrees with what was found before.

One of the interesting questions connected with the transition is whether there is any important difference of compressibility between the two forms. One might perhaps anticipate that the compressibility of the high pressure form would be markedly less than that of the low pressure form because there is such a large contraction of volume. The question may be answered by plotting first differences for 5,000 intervals as given in Table III against the mean pressure of the interval. It will be found, surprisingly, that the first difference curve for all three salts passes smoothly over the transition point; that is, there is no discontinuity large enough to be certainly established by these measurements in either $(\partial v/\partial p)_\tau$ or $(\partial^2 v/\partial p^2)_\tau$ on passing through the transition. Approximate calculations have been made by Jacobs[14] on the transitions of these salts; his calculations indicated no important change in $(\partial v/\partial p)_\tau$ at the transition.

RbCl. The rubidium halides all have transitions from the NaCl structure to presumably the CsCl structure[15] at pressures near 5,000. This is so low that no value can be attached to any confirmation by this work of the previous value[16] for the transition pressure, so no attempt was made to get it accurately. The changes of volume of the transition at room temperature found in this work should, however, be good. But at CO_2 temperature the transition for all three halides ran so sluggishly that the measured volume changes were almost certainly too small. Presumptive confirmation of this is the fact that improbably large reductions of thermal expansion with pressure are demanded by these values. It was therefore assumed for all three halides that the change of volume at the transition is the same at CO_2 temperature as at room temperature, and the compressions at the lower temperature above the transition pressure were accordingly corrected by the proper additive constant. This assumption checks with the approximate independence of temperature of the volume changes of the potassium halides; these latter transitions occur at 20,000, which permits pressure to be reduced far enough below the transition pressure to avoid error. The new value of the thermal expansion of the rubidium halides given by this assumption varies in an entirely reasonable way with pressure, again lending plausibility to the assumption.

The RbCl was old stock, used in previous measurements. Two set-ups were made at both room temperature and CO_2 temperature. At room temperature the extreme compressions at 50,000 were 0.2762 and 0.2775; at CO_2 temperature the corresponding figures were 0.2685 and 0.2744. The arithmetic average is given in Table IV. The compressions at 5,000 in this Table of the low pressure phase were set equal to that given by my former work;[17] the value at CO_2 temperature was obtained by linear extrapolation of the former values at 30° and 75°. The changes of volume at the transition at room temperature given in the Table above were, however, those given by the present work, used without adjustment. The transition pressure is given roughly in the table as 5,000; my previous value for it was 5,500. The present value for the fractional change of volume during the transition is 0.1406 against 0.144 previously. At CO_2 temperature the directly measured change of volume was 0.126, which was adjusted to 0.1406 as explained above.

TABLE IV

COMPRESSIONS OF THE RUBIDIUM HALIDES

Pressure kg/cm^2	RbCl $cm^3/2.849$ gm		RbBr $cm^3/3.391$ gm		RbI $cm^3/3.591$ gm	
	R. T.	CO_2 T.	R. T.	CO_2 T.	R. T.	CO_2 T.
5,000	.1701	.1678	.1673	.1666	.1667	.1641
10,000	.1882	.1861	.1879	.1864	.1918	.1879
15,000	.2043	.2022	.2056	.2032	.2133	.2082
20,000	.2184	.2166	.2207	.2176	.2315	.2253
25,000	.2310	.2289	.2342	.2303	.2472	.2399
30,000	.2422	.2397	.2462	.2415	.2609	.2526
35,000	.2522	.2490	.2570	.2515	.2726	.2637
40,000	.2612	.2573	.2670	.2609	.2831	.2738
45,000	.2694	.2648	.2762	.2694	.2925	.2833
50,000	.2768	.2714	.2848	.2774	.3009	.2921
Transitions						
Press.	5,000	5,000	4,600	4,600	4,050	4,050
Compressions at Transition	.0295	.0272	.0330	.0324	.0349	.0328
	.1701	.1678	.1655	.1649	.1614	.1593

Readings at pressures below the transition were not accurate enough to permit an answer to the question as to whether there is a change of compressibility at the transition.

RbBr. The RbBr was most kindly prepared by Prof. G. P. Baxter by reduction of $RbBrO_3$ originally supplied by MacKay. Prof. Baxter characterized the purity as "good." Two set-ups were made at both temperatures. At room temperature the compressions at 50,000 were 0.2846 and 0.2851, and at the lower temperature 0.2746 and 0.2801. At room temperature the extreme discrepancy was at 30,000, where the compressions were 0.2438 and 0.2481. The averaged values are given in Table IV. Each run gave the same transition pressure at both temperatures; for one run it was 4,200 and for the other 5,000. The average, 4,600, is taken in the table; the former value was 4,920. The compression of the low pressure phase just below the transition was adjusted to agree with the determination of Slater;[18] the value at CO_2 temperature was obtained by linear extrapolation downward of his temperature coefficient of compressibility above 30°. At room temperature the fractional volume change at the transition on the two set-ups was 0.1323 and 0.1327. At CO_2 temperature the directly observed value, given by one run only, the other run not giving a good value, was 0.1214. This was adjusted to 0.1325 as explained above. The value formerly obtained for the change of volume at the transition at room temperature was much smaller than this, only 0.110. The new value is doubtless better.

RbI. The material I again owe to Prof. Baxter, who prepared it from $RbIO_3$ from MacKay. He estimated the impurity spectroscopically as 5 per cent, mostly K and Cs. Two set-ups were made at each temperature. At room temperature the extreme compressions at 50,000 were 0.2996 and 0.3036, and at CO_2 temperature 0.2892 and 0.2950. The averaged values are given in Table IV. The compressions of the low pressure phase immediately below the transition point are taken from the work of Slater,[19] the value at CO_2 temperature by linear extrapolation from his work. The transition pressure at room temperature given above, 4,050, is the average of the two values 4,000 and 4,100, and agrees exactly with that found in my previous work. At CO_2 temperature the transition pressure was assumed to be the same, the accuracy of these measurements not justifying the inference that it is either higher or lower. The two values for the fractional change of volume of the transition at room temperature were 0.1263 and 0.1268. The previous value was 0.104, again much lower, as was the case with RbBr. The new value is doubtless better. At CO_2 temperature the directly measured value, 0.1183, was adjusted to 0.1265 as explained.

CsCl. The material was obtained from the Department of Chemistry of Cornell University a number of years ago. Two set-ups were made at each temperature. At room temperature the two compressions at 50,000 were 0.1561 and 0.1646, and at CO_2 temperature 0.1472 and 0.1571. The averaged values are given in Table V.

TABLE V

COMPRESSION OF THE CAESIUM HALIDES

Pressure kg/cm^2	CsCl cm^3/4.031 gm		CsBr cm^3/4.478 gm		CsI cm^3/4.547 gm	
	R. T.	CO_2 T.	R. T.	CO_2 T.	R. T.	CO_2 T.
5,000	.0255	.0245	.0287	.0279	.0351	.0330
10,000	.0479	.0457	.0537	.0519	.0647	.0608
15,000	.0676	.0644	.0756	.0730	.0902	.0851
20,000	.0850	.0809	.0949	.0912	.1120	.1064
25,000	.1006	.0957	.1120	.1075	.1313	.1254
30,000	.1146	.1092	.1274	.1220	.1485	.1422
35,000	.1272	.1212	.1408	.1351	.1640	.1570
40,000	.1387	.1321	.1532	.1473	.1781	.1704
45,000	.1496	.1423	.1645	.1585	.1909	.1822
50,000	.1596	.1514	.1748	.1689	.2025	.1928

The compressions have been previously measured to 12,000.[20] At 30° the former values at 5,000 and 10,000 were 0.0266 and 0.0481 respectively against 0.0255 and 0.0479 now.

CsBr. For the material I am much indebted to Professor G. P. Baxter, who worked it up from his stock of pure material specially for these measurements. Two set-ups were made at each temperature. At room temperature the two runs gave for the compressions at 50,000, 0.1700 and 0.1797, and at CO_2 temperature 0.1626 and 0.1752. The averaged values are given in Table V.

Previous values[21] for the compressions at 30° at 5,000 and 10,000 were 0.310 and 0.0547 respectively against 0.0287 and 0.0537 now.

CsI. The material was obtained from Professor G. P. Baxter a number of years ago; part of it had already been used in measurements of the linear compressibility.[22] Two set-ups were made at each temperature. At room temperature the two runs gave for the compressions at 50,000 0.2012 and 0.2038, and at CO_2 temperature 0.1897 and 0.1950. The averaged values are given in Table V.

Previous values[22] for the compressions at 30° at 5,000 and 10,000 were 0.0370 and 0.0638 against 0.0351 and 0.0647 now.

NH_4Cl. The material was from the regular stock of the Harvard Chemical Laboratory, highest commercial purity. Two set-ups were made at each temperature. At room temperature the two compressions at 50,000 were 0.1439 and 0.1472, and at CO_2 temperature 0.1289 and 0.1300. The averages are given in Table VI. The density used in the table is the I.C.T. value; Wyckoff's value would be 1.539.

TABLE VI

COMPRESSION OF THE AMMONIUM HALIDES

Pressure kg/cm^2	NH_4Cl cm^3/1.536 gm		NH_4Br cm^3/2.548 gm		NH_4I cm^3/2.887 gm	
	R. T.	CO_2 T.	R. T.	CO_2 T.	R. T.	CO_2 T.
5,000	.0269	.0217	.0257	.0244	.0316	.0321
10,000	.0489	.0395	.0487	.0462	.0590	.0582
15,000	.0668	.0545	.0694	.0656	.0822	.0804
20,000	.0818	.0675	.0880	.0829	.1019	.0989
25,000	.0949	.0794	.1049	.0984	.1188	.1144
30,000	.1070	.0906	.1203	.1124	.1332	.1279
35,000	.1176	.1010	.1340	.1250	.1456	.1397
40,000	.1278	.1111	.1465	.1364	.1570	.1504
45,000	.1372	.1207	.1576	.1466	.1676	.1608
50,000	.1462	.1301	.1676	.1557	.1775	.1702

Previous values[23] for the compression at 30° at 5,000 and 10,000 respectively were 0.0262 and 0.0490 against 0.0269 and 0.0489 above.

NH_4Br. The material was also the best from the regular stock of the Harvard Chemical Laboratory. Three set-ups were made at each temperature; the third set-up was made by inadvertence due to an error in a recording, but there is no reason why the results should not be as good as for the other two. At room temperature the range of compressions at 50,000 was 0.1614 to 0.1742, and at CO_2 temperature 0.1479 to 0.1602. The averaged values are given in Table VI. The density of the table, 2.548 is the I.C.T. value; Wyckoff's value would be 2.455.

Previous values[24] for the compression at 25° at 5,000 and 10,000 were 0.0289 and 0.0517 respectively against 0.0257 and 0.0487 now.

NH_4I. The material was the best from the regular stock from commercial sources of the Harvard Chemical Laboratory. Two set-ups

were made at each temperature. It is known from previous work[25] that there is a transition at room temperature at very low pressure, about 500 kg/cm^2, with a volume change of 14 per cent, from the NaCl to the CsCl structure. Even if it had been part of the program of this work, satisfactory values of the change of volume at the transition could not have been obtained, since the friction was so great that it was doubtful whether the reaction from the high to the low pressure form ran to completion on release of pressure. The values given in the table were obtained by a smooth extrapolation of the high pressure values through the transition back to zero. At CO_2 temperature the form stable at atmospheric pressure is the CsCl form, so that there was no such complication as at room temperature. In the table therefore all figures refer to the CsCl modification, as do also all the figures for NH_4Cl and NH_4Br. The density used was calculated directly from the lattice constant given in Wyckoff for the CsCl form at −17°, with no attempt to apply a temperature correction. At room temperature the two values for the compression at 50,000 were 0.1727 and 0.1808, and at CO_2 temperature 0.1658 and 0.1703. The averages are given in Table VI.

There seem to be no previous measurements for comparison at low pressures.

AgCl. The material was Merck's best stock, kept protected from the light. Two different set-ups were made at both temperatures. Previously[26] an obscure transition had been found in the region between 10,000 and 20,000 kg/cm^2, the transition pressure being near the lower limit at room temperature and near the upper limit at 150°. This transition ran more rapidly and was better defined at 150° than at room temperature. There seemed to be no appreciable difference of compressibility between the low and high pressure forms. The first set-up of the present series did not disclose the transition. In the previous work a sheath of lead had been used instead of indium. I thought it not impossible that the lead might have had some role in initiating the transition; accordingly in the second set-up a small quantity of lead was placed in contact with the AgCl. This was without effect, however. I do not think it is to be concluded that AgCl has no transition. The material was now different from before; it is quite conceivable that the transition was now spread out over a wider region of indifference because of the difference of material, and this would be capable of accounting for failure to find it at room temperature. At the lower temperature even the previous work would suggest that the sluggishness would be so high that it would be impossible to find.

TABLE VII

Compression of the Silver Halides

Pressure kg/cm^2	AgCl cm^3/5.589 gm		AgBr cm^3/6.548 gm		AgI cm^3/5.709 gm	
	R. T.	CO_2 T.	R. T.	CO_2 T.	R. T.	CO_2 T.
5,000	.0113	.0107	.0111	.0103	.1769*	.1753*
10,000	.0216	.0207	.0215	.0202	.1896	.1868
15,000	.0312	.0301	.0313	.0297	.2001	.1969
20,000	.0401	.0389	.0404	.0386	.2095	.2061
25,000	.0484	.0471	.0496	.0476	.2180	.2145
30,000	.0562	.0549	.0584	.0562	.2257	.2222
35,000	.0634	.0621	.0665	.0641	.2326	.2291
40,000	.0704	.0690	.0743	.0716	.2396	.2362
45,000	.0772	.0755	.0818	.0789	.2462	.2428
50,000	.0838	.0818	.0890	.0858	.2525	.2490

* Transition below this point.

At 50,000 the values for the compression given by the two set-ups were 0.808 and 0.867 at room temperature, and 0.827 and 0.0807 at carbon dioxide temperature.

The only previous value of the compressibility is by Richards and Jones.[27] They give 2.40 × 10^{-6} at 20° for the average over the first 300 kg/cm.^{2} Exactly the same value is given by extrapolation of the figures found here.

AgBr. The material was "c.p." stock from Eimer and Amend. Three set-ups were made and runs made at both temperatures. The second set-up had to be discarded, however, because the vessel ruptured almost at once after the conclusion of the run, and the approach of rupture was evidently foreshadowed in abnormal behavior.

Previous measurements[28] had shown a very small transition in AgBr as well as in AgCl. The location of the transition was roughly the same, as was also the general behavior. In the first set-up of the present work irregularities were found at both temperatures in the expected neighborhood, but the results were not clean cut enough to indicate with certainty the presence of a transition, nor, if there is a transition, to distinguish between a transition of the first or the second kind. The two other set-ups did not suggest a transition of any kind. The irregularity of the first set-up was so small that the final values were smoothed right across it.

At 50,000 the values for the compression given by the two set-ups that were retained were 0.0916 and 0.0864 at room temperature, and 0.0863 and 0.0853 at carbon dioxide temperature.

The compressibility has been previously determined only by Richards and Jones.[29] Their average value over the first 300 kg/cm^2 at 20° is 2.74 $\times 10^{-6}$ against 2.30 by extrapolation of the present values. I think it very probable that the low pressure values of the present work are too low.

AgI. The material was "c.p." stock from Mallinckrodt. AgI is known to have a very large transition in the general neighborhood of 2,000 kg/cm.[2] The course of the transition line and the parameters of the transition have been already determined.[30] The pressure of this transition is so low that the accuracy of the present work did not justify the attempt for any accurate values in this range. The present data should be used only for the volume decrements at 5,000 and above.

Although the pressure of the transition could not be found with any precision, nevertheless the first set-up should permit a fairly good value for the volume change during the transition. This is now found to be 0.0286 cm^3/gm, against the previous value 0.0239. The essential difference between this and the former work is that now the material had been subjected to a preliminary application of 50,000 before the transition was measured, whereas formerly pressure never exceeded 12,000. It is not unlikely that formerly the transition had not run to completion because of sluggish resistance in the finely divided parts of the material, so that the present value may well be much closer to the correct value. This matter has been discussed by Jacobs,[31] who finds the present value much closer to his result as determined by X-ray measurements.

Three set-ups were made at room temperature, and two at carbon dioxide temperature. At room temperature the extreme compressions at 50,000 were 0.2503 and 0.2537; at the lower temperature the corresponding figures were 0.2481 and 0.2502. The value given in the table for the compression at the lower temperature is adjusted so as to use the temperature coefficient given by the same two set-ups.

The compressibility has been previously measured only by Richards and Jones[32] who find 4.11 $\times 10^{-6}$ for the average value in the first 300 kg/cm^2 at room temperature. The measurements above give for the average compressibility over the first 5,000 kg/cm^2, subtracting the volume change during the transition, the value 2.78 $\times 10^{-6}$. Comparison between the two values is complicated by the fact that the figure 2.78 is averaged over two different modifications.

TlCl. The material was from Eimer and Amend, "c.p." stock. Three different set-ups were made at both temperatures, with three different vessels. At 50,000 the extreme compressions at room temperature were 0.1286 and 0.1329, and at carbon dioxide temperature 0.1191 and 0.1275.

TABLE VIII

COMPRESSION OF THE THALLIUM HALIDES

Pressure kg/cm^2	TlCl cm^3/7.029 gm		TlBr cm^3/7.539 gm		TlI cm^3/7.435 gm	
	R. T.	CO$_2$T.	R. T.	CO$_2$T.	R. T.	CO$_2$T.
5,000	.0202	.0198	.0226	.0217	.0273	.0272
10,000	.0383	.0375	.0426	.0409	.0510	.0506
15,000	.0544	.0533	.0606	.0582	.0714	.0707
20,000	.0688	.0672	.0763	.0735	.0891	.0878
25,000	.0818	.0797	.0903	.0872	.1041	.1027
30,000	.0936	.0907	.1026	.0990	.1173	.1156
35,000	.1042	.1005	.1131	.1092	.1286	.1268
40,000	.1139	.1093	.1224	.1182	.1387	.1371
45,000	.1230	.1170	.1306	.1260	.1475	.1468
50,000	.1313	.1240	.1377	.1328	.1554	.1553

The compressibility appears to have been measured previously only by Richards[33] at room temperature in the range up to 300 kg/cm.[2] His average value in this range was 4.9 $\times 10^{-6}$ against the initial value 4.3 $\times 10^{-6}$ extrapolated from the present high pressure measurements.

TlBr. The material was obtained from MacKay, made especially for this work. Two set-ups were made at both temperatures. At room temperature the compressions at 50,000 were 0.1340 and 0.1399; the corresponding figures at carbon dioxide temperature were 0.1261 and 0.1382. The discrepancy at the lower temperature is greater than usual, which means that the temperature coefficient of compression has less reliability.

The only previous value of the compressibility appears to be by Richards,[34] who found for the average compressibility up to 300 kg/cm^2 at room temperature 5.3 $\times 10^{-6}$, to be compared with 4.8 $\times 10^{-6}$ given by extrapolation of the values in the table.

TlI. The material was from Eimer and Amend, "c.p." stock. Two set-ups were made at both temperatures. At room temperature the two compressions at 50,000 were 0.1538 and 0.1556; at carbon dioxide temperature the corresponding figures were 0.1513 and 0.1580.

The compressibility has been previously measured by Richards and Jones,[36] who found 5.3 × 10^{-6} for the average value over the first 300 kg/cm^2 at room temperature. It is to be noticed that this value is the same as for TlBr, and therefore perhaps somewhat improbable. The value given by extrapolation of the high pressure results is 5.9 × 10^{-6}.

CaS. The material was commercial "c.p." stock from Eimer and Amend. Runs were made with two different set-ups at both temperatures. At room temperature the compressions of the two runs at 50,000 were 0.0703 and 0.0778; at carbon dioxide temperature the corresponding figures were 0.0604 and 0.0705. The temperature coefficient cannot be very good.

TABLE IX

COMPRESSIONS OF CALCIUM SULFIDE, SELENIDE, AND TELLURIDE

Pressure kg/cm^2	CaS cm^3/2.617 gm		CaSe cm^3/3.837 gm		CaTe cm^3/4.365 gm	
	R. T.	CO_2 T.	R. T.	CO_2 T.	R. T.	CO_2 T.
5,000	.0129	.0113	.0100	.0094	.0111	.0103
10,000	.0240	.0217	.0190	.0177	.0210	.0193
15,000	.0337	.0307	.0271	.0255	.0298	.0274
20,000	.0421	.0385	.0345	.0324	.0377	.0349
25,000	.0493	.0452	.0415	.0387	.0450	.0419
30,000	.0555	.0509	.0482	.0447	.0519	.0486
35,000	.0610	.0559	.0545	.0504	.0586	.0549
40,000	.0658	.0602	.0605	.0552	.0650	.0611
45,000	.0700	.0641	.0662	.0596	.0713	.0669
50,000	.0740	.0677	.0718	.0636	.0773	.0727

The density used in the calculations was 2.617, as given by Wyckoff from X-ray measurements. It is to be noticed that there is a rather wide divergence in an unusual direction between this figure and that given by Mellor from chemical data, namely 2.80. I have previously made measurements on the compressibility of the compressed powder[36] to 12,000 kg/cm^2. The compressions formerly found at 5,000 and 10,000, were 0.105, 0.190, against 0.0118 and 0.0220 above. It is to be remarked that the second degree term in the previous expression gives impossible values above 30,000.

CaSe. The material was synthesized from the elements in a welded iron tube at 950° C. An attempt to have this material specially prepared by a well known chemical supply house was a failure, the material supplied by them being highly impure. The same remark applies to calcium telluride, and to the selenides and tellurides of strontium and barium. Runs were made with two set-ups at both temperatures. At room temperature the compressions at 50,000 were 0.0753 and 0.0683; at carbon dioxide temperature they were 0.0600 and 0.0672.

There are no previous values of compressibility for comparison.

CaTe. The material was synthesized from the elements in iron at 950°. Runs were made with two set-ups at both temperatures. At room temperature at 50,000 the compressions were 0.0683 and 0.0753; at carbon dioxide temperature the compressions were 0.0600 and 0.0672.

There are no previous measurements of compressibility. It is to be remarked that Mellor gives a figure for the density 4.87, by Haase, much higher than the X-ray value 4.365 given by Wyckoff, which was used in the calculations.

SrS. The material was "c.p." stock from Eimer and Amend. Runs were made with two set-ups at both temperatures. At room temperature the compressions at 50,000 were 0.0802 and 0.0845, and at carbon dioxide temperature 0.0624 and 0.0717.

TABLE X

COMPRESSIONS OF STRONTIUM SULFIDE, SELENIDE, AND TELLURIDE

Pressure kg/cm^2	SrS cm^3/3.935 gm		SrSe cm^3/4.58 gm		SrTe cm^3/5.256 gm	
	R. T.	CO_2 T.	R. T.	CO_2 T.	R. T.	CO_2 T.
5,000	.0170	.0139	.0114	.0109	.0143	.0121
10.000	.0309	.0251	.0213	.0205	.0269	.0234
15,000	.0424	.0356	.0301	.0291	.0386	.0340
20,000	.0516	.0438	.0380	.0369	.0490	.0439
25,000	.0593	.0505	.0454	.0442	.0586	.0533
30,000	.0658	.0558	.0525	.0511	.0675	.0618
35,000	.0705	.0597	.0589	.0574	.0755	.0697
40,000	.0754	.0629	.0653	.0639	.0833	.0768
45,000	.0793	.0655	.0714	.0701	.0904	.0832
50,000	.0830	.0677	.0775	.0764	.0971	.0888

The compressibility has been previously measured[37] on the compressed powder up to 12,000 kg/cm^2. The compressions found at 5,000 and 10,000 were 0.0109 and 0.0200. These are so much lower than the values found in the present work that some difference in the material is indicated.

SrSe. Two different batches of material were used. The first was made specially to order by a chemical supply house. With this two set-ups were made, separated by an interval of about a month. The first set-up gave the abnormally high compression of 0.33 at 50,000 kg/cm² with a well marked polymorphic transition near 30,000 with a volume change of 1.2 per cent. The second set-up, a month later, gave a compression at 50,000 of only 0.24, and the transition at 30,000 now gave only an 0.6 per cent change of volume. The explanation obviously was chemical instability in the original material. It would be interesting to identify the compound that has the transition. Metallic strontium has a transition at a pressure which would permit, by some stretch of the imagination, identification of it as the material, but its volume change, which is only 0.9 per cent, is so small as apparently to rule this out.

A second batch of material was now synthesized by me from the elements in a welded iron tube at 950° C. Two set-ups were made with this at both temperatures. The compressions were now very much less and the transition had disappeared, so that the probability is that SrSe was at least more nearly approximated. At room temperature the two compressions at 50,000 were 0.0687 and 0.0849; at carbon dioxide temperature they were 0.0690 and 0.0825. The discrepancy between the runs is unusually large, and probably indicates chemical instability. The smaller compressions were obtained with the second set-up, made some two weeks after the first. It is probable, therefore, that the true compressions of the compound are on the high side of the average as given in the table. Decomposition of the selenide with formation of strontium oxide would appear to be a plausible explanation.

There are no previous compressibilities for comparison.

SrTe. The material was synthesized from the elements in the same way as the selenide. Two set-ups were made at both temperatures. The compressions at room temperature at 50,000 were 0.0837 and 0.1091; at carbon dioxide temperature they were 0.0776 and 0.0985. Again the differences are so large as to point to some change in the material. Here the larger compressions were obtained with the second set-up, but the situation here differs from that with SrSe in that now the two runs were separated only by one day whereas formerly the interval had been two weeks. Decomposition to metallic strontium, the oxide now not having time to form in appreciable quantities, would explain the variation in compression.

Before the two runs with the synthesized material, one set-up was made with material furnished by the chemical supply house. The compression given by this at room temperature at 50,000 was 0.1159. This is higher than the value for the synthesized material, and thus differs in the same direction as was previously found for the selenide, but by a very much smaller amount. The results obtained with this set-up were not used in taking the average.

BaS. The material was "c.p." stock from Eimer and Amend. Two set-ups were made at each temperature. At room temperature the two compressions at 50,000 were 0.0861 and 0.0848; the corresponding figures at carbon dioxide temperature were 0.0776 and 0.0903. It is evident that not much weight can be attached to the temperature coefficient.

TABLE XI

COMPRESSIONS OF BARIUM SULFIDE, SELENIDE, AND TELLURIDE

Pressure kg/cm²	BaS cm³/4.25 gm		BaSe cm³/4.956 gm		BaTe cm³/5.168 gm	
	R. T.	CO_2 T.	R. T.	CO_2 T.	R. T.	CO_2 T.
5,000	.0133	.0129	.0133	.0118	.0154	.0137
10,000	.0251	.0244	.0251	.0225	.0293	.0262
15,000	.0357	.0347	.0357	.0322	.0418	.0378
20,000	.0450	.0441	.0449	.0408	.0531	.0484
25,000	.0535	.0527	.0533	.0487	.0635	.0581
30,000	.0612	.0604	.0610	.0558	.0730	.0670
35,000	.0682	.0673	.0681	.0623	.0818	.0751
40,000	.0747	.0737	.0745	.0683	.0898	.0826
45,000	.0806	.0793	.0816	.0739	.0976	.0895
50,000	.0861	.0846	.0882	.0793	.1049* .1128	.0957* .1057

* Transition.

I have previously[38] measured the compressibility of similar material up to 12,000. For the compressions at 30° this previous work gives 0.0132 and 0.0237 at 5,000 and 10,000 respectively, against .0133 and .0251 now.

BaSe. At first I attempted to use material which had been specially prepared by a chemical supply house. This, however, was so unstable that it exploded on being rammed into the pressure vessel preparatory to a run. Material was accordingly synthesized from the elements in a sealed iron tube at 950°, in exactly the same way as for the other compounds of this class. This material appeared homogeneous and satisfactory enough, but it also has an unusual degree of chemical instability, as shown by its liability to spontaneously catch fire in the air from the heat of the lathe tool with which the iron envelope is turned off. However, by operating slowly and with a sharp tool this difficulty can be avoided.

Two set-ups at both temperatures were made with the synthesized material. At room temperature the compressions at 50,000 were 0.0798 and 0.0951; the corresponding figures at carbon dioxide temperature were 0.0701 and 0.0872.

There are no previous measurements of compressibility.

BaTe. The first set-up was made with specially prepared material from the chemical supply house. This gave a polymorphic transition between 40,000 and 45,000 with volume change beetween 2 and 3 per cent. Tellurium is known to have a transition in this pressure range.[39] Since the volume change of this transition is "large" it is not improbable that the effect observed is to be explained by a partial decomposition into the elements.

After this unsuccessful attempt, the compound was synthesized in the regular way from the elements, and two set-ups made at both temperatures. Both set-ups gave a polymorphic transition at both temperatures at a pressure so near the end of the range that there could be no assurance that the transition had run to completion. The volume change given by the readings is therefore almost certainly too low. In the table the larger of the volume changes given by the two set-ups is retained. There is no reason to think that there is any connection between this transition and that observed with the other material. The fact that the synthesized material gave no indication of a transition in the neighborhood of that of tellurium shows that any decomposition must have been unimportant.

The compressions (of the low pressure phase) at 50,000 at room temperature were 0.0986 and 0.1098; at carbon dioxide temperature they were 0.0892 and 0.1009.

There seem to be no previous measurements of compression for comparison.

PbS. The material was powder from Kahlbaum. Three set-ups were made at both temperatures. At room temperature the compressions at 50,000 were 0.1048, 0.0895, and 0.1018; at carbon dioxide temperature they were 0.1055, 0.0814, and 0.0928. It is to be noticed that at room temperature two of the determinations agree very well, with the third markedly divergent. One would perhaps be tempted to discard the divergent run altogether. But the difference, although large, is occasionally equaled by other substances, and furthermore at the lower temperature the three set-ups gave uniformly scattering results. The results of all three runs were accordingly averaged on an equal footing.

PbS has a well marked transition not known before at both temperatures at about the middle of the pressure range. This is shown in Table XII by the figures in brackets. The bracketed

TABLE XII

Compressions of Lead Sulfide, Selenide, and Telluride

Pressure kg/cm^2	PbS cm^3/7.472 gm		Pressure kg/cm^2	PbSe cm^3/8.22 gm		Pressure kg/cm^2	PbTe cm^3/8.732 gm	
	R. T.	CO_2 T.		R. T.	CO_2 T.		R. T.	CO_2 T.
5,000	.0101	.0101	5,000	.0153	.0136	5,000	.0134	.0131
10,000	.0200	.0197	10,000	.0289	.0262	10,000	.0255	.0251
15,000	.0294	.0287	15,000	.0413	.0379	15,000	.0366	.0361
20,000	.0383	.0372	20,000	.0523	.0487	20,000	.0469	.0464
24,680	.0464	.0419	25,000	.0621	.0585	25,000	.0564	.0558
22,770	.0663	.0634						
25,000	.0671	.0668	30,000	.0711	.0674	30,000	.0650	.0642
30,000	.0752	.0739	35,000	.0789	.0754	35,000	.0731	.0716
35,000	.0822	.0799	40,000	.0855	.0826	40.000	.0802	.0783
40,000	.0885	.0851	43,320	.0903	.0838	41,200	.0818	
			43,360	.1067	.0938		.0912	
45,000	.0939	.0895	45,000	.1099	.0976	45,000	.0952	.0842
50,000	.0988	.0934	50,000	.1183	.1060	50,000	.0998	.0896

pressures are the transition pressures, the upper of the two figures being for room temperature.

The compression has been previously measured[40] up to 12,000. The previous compressions at 30° at 5,000 and 10,000 were 0.00902 and 0.01774, against 0.0101 and 0.0200 now. These values are distinctly lower than found now. The former material was a single flawless natural crystal of galena; the difference may well be due to the difference of material.

PbSe. The material was especially made by MacKay. Two set-ups were made at both temperatures. There is a transition at both temperatures between 40,000 and 45,000 with a volume change between one and two per cent. This transition is sluggish, and there could be no assurance that it ran to completion. One of the set-ups gave a considerably larger volume change than the other. The larger value was used for the final results. The "average" volume changes at 45,000 and 50,000 listed in Table XII were obtained by correcting the result given by the set-up which showed the larger change at the transition by one half the difference between the two set-ups at 40,000. At room temperature the compressions of the two set-ups at 45,000 differed by 0.0057, and at carbon dioxide temperature by 0.0023.

Previous measurements[41] have been made up to 12,000 on material synthesized by heating the elements together in quartz and slowly cooling to avoid blow holes. The compressions at 30° at 5,000 and 10,000 were 0.0100 and 0.0194, 33 per cent lower than the values found above. There is no reason to suspect important chemical impurities in either material, but the earlier sample may well have been nearly all crystalline, while the material of the high pressure measurements may have had a considerable fraction of amorphous material. It could not have been all amorphous, however, or it would have had no transition.

PbTe. This material was also specially made by MacKay. Two set-ups were made at both temperatures. Both set-ups showed a sluggish transition beetween 40,000 and 45,000. The same remarks apply to this transition as to that of PbSe: the one set-up gave a larger volume change than the other. This was 0.8 per cent, and this value was used in the final average. Neither set-up showed any transition at carbon dioxide temperature, probably because of too great sluggishness. The two set-ups differed by more than the usual amount, the difference at 50,000 of the compressions being 0.015 at both temperatures.

The compression of PbTe has been previously measured[42] to 12,000. The former values for the compression at 30° at 5,000 and 10,000 were 0.0120 and 0.0230 respectively, smaller than the values found now. The difference is probably to be attributed in large part to a larger fraction of amorphous material in the present measurements. The fraction of amorphous material is probably, however, not nearly as large as it was for PbSe.

ZnS. Five set-ups in all were made with this material. The first three were made with commercial "c.p." material, finely divided precipitated powder. These three set-ups gave unusually concordant results, considering the smallness of the absolute compression; the compression at 50,000 varied from 0.0643 to 0.0685. In spite of the consistency of the results the compressions at 5,000 and 10,000 were almost twice as large as had been found previously[43] in measurements on a natural crystal of sphalerite (ZnS) up to 12,000. An X-ray analysis of the material was accordingly made by Dr. Greninger, who found that a large fraction of it was the hexagonal modification, wurtzite, instead of the cubic sphalerite. The density of wurtzite is only 0.37 per cent less than that of sphalerite, so that so large a difference of compressibility is hardly to be anticipated. I had previously found that wurtzite is completely converted into sphalerite by a combination of shearing stress and hydrostatic pressure. Apparently no such conversion took place under the more nearly hydrostatic conditions of these measurements. It is to be remarked that in virtue of the greater compressibility of wurtzite the density of wurtzite becomes greater than that of sphalerite above a few thousand kilograms, so that the conversion is inhibited instead of assisted by pressures above this magnitude.

Two set-ups were now made with a clear natural crystal of sphalerite, and at once the smaller values previously found were obtained. This substance has the smallest compressibility of any measured in this paper, so that a smaller relative accuracy is to be anticipated. The agreement was, however, better than for many other substances. At room temperature the two compressions at 50,000 were 0.0463 and 0.0514; at carbon dioxide temperature the figures were 0.0520 and 0.0545. The set-up which gave the figure 0.0520 did not give good values beyond 35,000 at carbon dioxide temperature, there evidently being excessive in-

TABLE XIII

Compressions of Zinc Sulfide, Selenide, and Telluride

Pressure kg/cm²	ZnS cm³/4.10 gm		Pressure kg/cm²	ZnSe cm³/5.322 gm		Pressure kg/cm²	ZnTe cm³/5.736 gm	
	R. T.	CO_2 T.		R. T.	CO_2 T.		R. T.	CO_2 T.
5,000	.0063	.0067	5,000	.0121	.0106	5,000	.0119	.0121
10,000	.0123	.0129	10,000	.0224	.0203	10,000	.0226	.0228
15,000	.0179	.0189	15,000	.0316	.0287	15,000	.0323	.0325
20,000	.0231	.0247	20,000	.0392	.0360	20,000	.0413	.0413
25,000	.0281	.0303	25,000	.0454	.0426	25,000	.0499	.0499
30,000	.0328	.0355	30,000	.0506	.0483	30,000	.0581	.0578
35,000	.0372	.0404	35,000	.0549	.0530	35,000	.0661	.0655
40,000	.0414	.0453	38,470	.0568	.0539		.0740	.0673
45,000	.0455	.0500	36,360	.0607	.0562		at 40,000	.0718
							.0763	Transition
							.0812	at 36,660
50,000	.0495	.0545	40,000	.0617	.0581		Transition	.0768
							at 41,270	at 40,000
			45,000	.0656	.0612	45,000	.0860	.0831
			50,000	.0693	.0646	50,000	.0931	.0893

ternal friction, and the figures given in the Table were obtained by an adjusted extrapolation. The results for sphalerite are given in Table XIII. The results for the powdered material are not given, in spite of their consistency, because of indefiniteness in the relative amounts of sphalerite and wurtzite.

The values previously found for the compression at 30° at 5,000 and 10,000 were 0.0064 and 0.0126, against 0.0063 and 0.0123 found now. Previously a break was found at 30° in the neighborhood of 9,000, which was taken to indicate an obscure transition. If the effect is real it is beyond the sensitiveness of the present measurements, for no such effect was detected.

ZnSe. A first set-up was made with material made specially by a commercial house. The results were smooth enough, but the appearance of the material was suspicious, and this was confirmed by an X-ray analysis by Dr. Greninger, who found a fairly large fraction of free zinc. I accordingly attempted to synthesize it from the elements myself. At first only a very small yield was obtained under a variety of conditions, in quartz and in iron at temperatures from 500° to 1100° C. For these attempts massive slugs of zinc and of selenium of the proper weights were sealed together into the heated enclosure. Success was finally achieved only by finely dividing the material, using fine zinc filings intimately mixed with powdered selenium. These were welded into an iron tube with very little free space and held at 1050° for 2.5 hours. A chemical analysis, for which I am indebted to Mr. A. A. Kasper of the Harvard Chemistry Department, showed 8.8 per cent of iron, and 1.0 per cent of free selenium. The final results are corrected for these impurities.

Two set-ups were made with this synthetic material. At pressures above 35,000 there was a highly unusual amount of irregularity. The most plausible explanation of these irregularities is that there is a very sluggish polymorphic transition with small volume change, the high pressure form having an unusually great rigidity or internal friction, resulting in an unusually large difference between the increasing and the decreasing curves. This frictional effect was so large with one of the set-ups that the results obtained with it above the presumptive transition point could not be used, but the results given in the table above the transition are obtained from only one set-up, making an additive correction to bring the results into agreement with the average of the two set-ups at 35,000. Up to 35,000 the agreement between the two set-ups was as good or better than usual, considering the smallness of the effect. At room temperature the two compressions at 30,000 were 0.0500 and 0.0512; at carbon dioxide temperature the figures were

0.0479 and 0.0487. In Table XIII the transition data are bracketed; the upper of the two pressures is the transition pressure at room temperature.

There seem to be no previous measurements of compression for comparison.

ZnTe. The first set-up on specially prepared material obtained from a chemical supply house gave results of a suspiciously high compressibility with a transition of fairly large volume change at very nearly the pressure of a known transition of tellurium. I accordingly synthesized the material myself from spectroscopically pure elements in quartz at 950° for 1.5 hours. The material was apparently perfectly homogeneous. Liquid tellurium and zinc both have a high fluidity and there was apparently no such difficulty as had been found with the selenium which had necessitated finely dividing the materials.

Two set-ups were made with this synthetic material. Both gave at room temperature a transition just above 40,000, but with a much smaller volume change than found with the first material. It is a coincidence that metallic tellurium and the compound have a transition at about the same pressure. At 50,000 the compressions given by the two set-ups were 0.0884 and 0.0962. Part of the difference is without doubt due to incomplete running of the transition on one of the set-ups. In the results in Table XIII the larger of the two changes of volume was used, and the averages above the transition pressure corrected by the constant difference. Of course even the larger of the two volume changes may well be too small. At carbon dioxide temperature the transition with one of the set-ups was so sluggish that no certain values could be obtained for it, and only the values of the other set-up, with a constant correction, were used above the transition point. At 35,000, just below the transition, the two set-ups gave at carbon dioxide temperature 0.0630 and 0.0674 for the compressions. In Table XIII the transition data are intercalated in the columns in an obvious enough fashion.

HgS. This compound occurs in two forms. The black is cubic, formed by processes of chemical precipitation at relatively low temperatures, is comparatively unstable, being converted into the other form by heating, and is of doubtful occurrence in nature. The other form is red, hexagonal, occurs as a mineral in nature, and is produced artificially at higher temperatures. Since all the other measurements of this paper have been made on cubic compounds I naturally desired to make the compression measurements on the black modification. Considerable effort was spent on this, but without success. The black modification was invariably converted by the preliminary application of 50,000 to the red. The details of the transformation were not investigated further.

Measurements at high pressure therefore must of necessity be made on the red hexagonal modification. The material was from Eimer and Amend, "c.p." stock. Two set-ups were made. At room temperature the two compressions at 50,000 were 0.1082 and 0.1089; at carbon dioxide

TABLE XIV

COMPRESSIONS OF MERCURIC SULFIDE, SELENIDE, AND TELLURIDE

Pressure kg/cm^2	HgS (red) cm^3/8.10 gm		Pressure kg/cm^2	HgSe cm^3/8.312 gm		HgTe
	R. T.	CO$_2$ T.		R. T.	CO$_2$ T.	
5,000	.0241	.0224	5,000	.0090	.0085	Decomposes to the elements under pressure. At room temperature there is a transition with an 8.4 per cent volume change at 12,800 kg/cm^2
10,000	.0427	.0399	7,650	.0130		
15,000	.0570	.0539	7,220	.1090	.0131	
					.1057	
20,000	.0682	.0651	10,000	.1152	.1139	
25,000	.0776	.0741	15,000	.1275	.1271	
30,000	.0854	.0814	20,000	.1378	.1383	
35,000	.0920	.0875	25,000	.1472	.1481	
40,000	.0980	.0929	30,000	.1555	.1567	
45,000	.1035	.0973	35,000	.1626	.1640	
50,000	.1085	.1014	40,000	.1692	.1705	
			45,000	.1751	.1760	
			50,000	.1804	.1812	

temperature they were 0.0940 and 0.1088. The agreement at room temperature is unusually good; the temperature coefficient is obviously uncertain.

There seem to be no previous measurements of compression for comparison.

HgSe. A set-up with material specially prepared by a chemical supply house gave suspiciously high results. Accordingly the material was synthesized from the elements in quartz at 950°, giving a homogeneous appearing product. With this two set-ups were made. There is a large and cleanly running transition near 7500. The two set-ups gave for the volume change at 50,000 at room temperature 0.1782 and 0.1826; the corresponding figures at carbon dioxide temperature were 0.1828 and 0.1796.

There appear to be no previous measurements of the compression for comparison.

HgTe. This was synthesized from the elements in quartz. Accurate measurements were found to be impossible because it decomposes into the elements under pressure. HgTe is highly unusual in that it is formed from the elements with expansion; decomposition will therefore be facilitated by pressure. The decomposition is comparatively slow, however, so that measurements of a sort could be made. The compound has at 22° a transition with large volume change, 8.4 per cent, at 12,800 kg/cm^2. This pressure is very near the freezing pressure of mercury (12,000) at the same temperature, so that the calculation of the transition data was complicated by this effect. However, the volume change at the transition is 6.5 times greater than the volume change which would have arisen from the freezing of the mercury resulting from a complete decomposition into the elements, so that qualitatively there is no confusion from this complicating factor. By comparing the volume change of the transition with increasing and decreasing pressure it was possible to estimate that decomposition could not have been as much as one quarter completed by two excursions to 50,000 and back. The volume expansion on formation from the elements is 9.95 per cent at atmospheric pressure. A large part of this expansion is annulled by the transition, so that above the transition the tendency to pressure decomposition must be very much reduced.

The compression of HgTe has been previously measured[14] to 12,000. In this range no decomposition appeared, but an unusual irregularity of the results was noted, which it now appears may have been due to beginning decomposition. The compression previously found at 5,000 was 0.0093, somewhat greater than that of HgSe and thus in the expected direction, but still so small in amount as not to be safely beyond experimental error.

It is plausible to suppose that the transitions of both HgSe and HgTe are from the cubic form known to be stable at atmospheric pressure to the hexagonal form of red HgS. The very much greater compressibility of the red HgS than either the cubic HgSe or HgTe is to be noted. The table shows that the compressibility of HgSe takes a large upward jump on passing from the low pressure to the high pressure form, and this in spite of the decrease of volume. This is consistent with the suggestion that the high pressure forms of HgSe and HgTe are analogous to the hexagonal form of HgS.

Incidentally the measurements on HgTe afforded a confirming measurement on the high pressure transition of mercury which has been previously studied.[45] There was a sufficient amount of free mercury formed by decomposition to permit a determination of the pressure of the transition at room temperature (21.8°). This was found to be 35,000 kg/cm^2, agreeing with the former value 34,460 within the limits of error of the present determination.

This completes the measurements of simple binary compounds. There follows now measurements on several elements the compressibility of which is high enough to give fairly accurate results with this apparatus.

Sulfur. The material was clear single crystal material, which I had prepared a number of years ago by slow crystallization from a CS_2 solution. Two set-ups were made at each temperature. At room temperature the two compressions at 50,000 were 0.2018 and 0.1904; at carbon dioxide temperature the corresponding figures were 0.1851 and 0.1722.

Rough measurements have previously[46] been made of the compression up to 45,000 kg/cm^2. The agreement with the present values is very close up to 25,000, but beyond that the former values become larger, being 0.195 at 45,000 against the present 0.189. One of the two present runs agreed with the former results almost exactly over the entire range.

Selenium. The material I owe to the courtesy of the American Smelting and Refining Co., who had especially purified it. It was provided in the form of powder. For these measurements I sealed

TABLE XV

COMPRESSIONS OF SULFUR, SELENIUM, AND TELLURIUM

Pressure kg/cm²	Sulfur cm³/2.07 gm		Selenium cm³/4.875 gm		Tellurium cm³/6.316 gm	
	R. T.	CO₂ T.	R. T.	CO₂ T.	R. T.	CO₂ T.
5,000	.0476	.0398	.0490	.0447	.0256	.0235
10,000	.0833	.0720	.0893	.0813	.0458	.0420
15,000	.1104	.0980	.1226	.1117	.0629	.0575
20,000	.1316	.1187	.1490	.1362	.0774	.0711
25,000	.1485	.1350	.1702	.1355	.0908	.0836
30,000	.1620	.1477	.1865	.1697	.1018	.0953
35,000	.1728	.1576	.1987	.1803	.1129	.1065
40,000	.1817	.1657	.2081	.1897	.1225	.1170
					*	†
45,000	.1894	.1726	.2175	.1987	.1817	.1709
50,000	.1961	.1786	.2265	.2071	.1907	.1810

* Transition at 40,130. Compressions at transition 0.1227 and 0.1724.

† Transition at 41,160. Compressions at transition 0.1193 and 0.1629.

it into pyrex, melted it with a bunsen burner until the evolution of bubbles of gas had practically ceased, allowed it to cool in the air, and then chilled the tube in liquid air so as to make separation from the glass easier. The product was a shiny black glass. Two set-ups were made at each temperature. One might be prepared to find some permanent change produced by the application of pressure, but there was no evidence of this. At room temperature and 50,000 the two set-ups gave 0.2311 and 0.2219 for the compression, and at carbon dioxide temperature 0.2116 and 0.2027.

The value of the density used in the calculations was 4.875, calculated from the X-ray determinations given in Wyckoff. Much lower figures are often quoted; these doubtless refer to the glassy as distinguished from the crystallized condition, and might well be more appropriate to use in the present circumstances.

If the differences of compression for 5,000 intervals are plotted, a very distinct break in the direction of the curve will be found near 34,000. This is a quite unmistakable phenomenon; it occurs at both temperatures, and was shown by both set-ups with close quantitative agreement. It seems plausible to suppose that it is connected with a taking of the "slack" out of the intermolecular spaces of the glass by the operation of pressure. It cannot be a crystallization phenomenon, for such would be irreversible, and no such effects were found. It amounts to a discontinuity in $(\partial^2 v/\partial p^2)_T$, and is to be described formally as a transition of the third kind.

There are no previous measurements to high pressures for comparison. The average compressibility between 100 and 500 kg/cm² has been found by Richards, Stull, and Brink[47] to be 11.6×10^{-6} against 10.6×10^{-6} by extrapolation of the present high pressure values.

Tellurium. The material was purified by the Research Department of the Raritan Copper Works some 15 years ago, and has been in my stock since. I had removed the gas from it by prolonged melting in high vacuum. Two set-ups were made at both temperatures. There is a transition, which was known before,[48] with a volume change of 5 per cent, near 40,000. The range above this is rather short for giving the compressibility of the high pressure modification, particularly when one considers the width of the region of indifference. One of the set-ups did not give as good values as the other; the first differences for the poorer set-up above the transition were extrapolated from the values below the transition. The better set-up gave no evidence for any important change in compressibility on passing through the transition. At room temperature the values for the total compression at 50,000 were 0.1979 and 0.1835; the corresponding figures at carbon dioxide temperature were 0.1875 and 0.1745.

Previous measurements[49] of the compression in the range up to 12,000 give for the compressions at 5,000 and 10,000 0.0231 and 0.0418 respectively, against the present values 0.0256 and 0.0458.

Antimony. The material was Kahlbaum's "K" grade, obtained a number of years ago. It had been further purified by making it into single crystals from the melt. For these measurements it was cast in pyrex, and turned to dimensions. Two set-ups were made at both temperatures. At room temperature the two compressions at 50,000 were 0.0977 and 0.0995; at carbon dioxide temperature they were 0.0932 and 0.0958.

A transition is to be looked for, because of the chemical similarity between antimony and bismuth. A previous exploration[50] with a less sensitive earlier form of apparatus had given negative results. No evidence for it was found now with the present more sensitive apparatus. Some evidence for it has been found in explorations with the shearing apparatus.[50] It is not impossible that the transition is suppressed by viscous effects in these more nearly hydrostatic conditions.

TABLE XVI

COMPRESSION OF ANTIMONY

Pressure kg/cm^2	ΔV cm^3/6.684 gm	
	R. T.	CO$_2$ T.
5,000	.0130	.0123
10,000	.0249	.0234
15,000	.0362	.0338
20,000	.0465	.0434
25,000	.0565	.0526
30,000	.0659	.0615
35,000	.0747	.0701
40,000	.0829	.0783
45,000	.0910	.0865
50,000	.0986	.0945

The compreession has been previously measured[51] to 12,000. The former values of the compression at 5,000 and 10,000 were 0.0127 and 0.0239 against 0.0130 and 0.0249 above.

Bismuth. The material is the same as used in a number of my other measurements, most recently for the determination of a pressure fixed point.[2] It had been purified a number of years ago by a double electrolytic deposition. Three set-ups were made at both temperatures. The first of these gave values much too high for some unknown reason, and was discarded. The compressions given by the two set-ups that were retained were at 50,000 and room temperature 0.1743 and 0.1775; the corresponding figures at carbon dioxide temperature were 0.1746 and 0.1768. The results are given in Table XVII.

Bismuth has three new polymorphic forms at high pressure. The transitions from I to II and from II to III occur so nearly at the same pressure that it was beyond the resolving power of this apparatus to attempt to separate them. The transition pressures given in the table were the mean results obtained with this apparatus; better values have been found before with more suitable apparatus.[52] The high pressure transition, from III to IV, on the other hand is probably characterized better by the values given in the table than I have been able to do before. In any event, the variation of the transition pressure with temperature is very uncertain because of the great sluggishness.

The compression has been previously measured[53] in the range to 12,000. The former compressions at 5,000 and 10,000 were 0.0141 and 0.0270 against 0.0144 and 0.0279 now.

TABLE XVII

COMPRESSION OF BISMUTH

Pressure kg/cm^2	ΔV cm^3/9.80 gm	
	R. T.	CO$_2$ T.
5,000	.0144	.0137
10,000	.0278	.0265
15,000	.0407	.0390
20,000	.0524	.0509
25,000	.0639	.0622
27,570	.0692 .1538	
28,020		.0689 .1540
30,000	.1565	.1560
35,000	.1619	.1609
40,000	.1661	.1652
40,740	.1676 .1700	
41,260		.1666 .1695
45,000	.1729	.1725
50,000	.1759	.1757

TABLE XVIII

COMPRESSION OF RUBBER

Pressure kg/cm^2	ΔV cm^3/1.91 gm	
	R. T.	CO$_2$ T.
5,000	.1300	.0794
10,000	.1800	.1235
15,000	.2146	.1538
20,000	.2345	.1772
25,000	.2535	.1958
30,000	.2700	.2119
35,000	.2845	.2254
40,000	.2960	.2364
45,000	.3050	.2460
50,000	.3124	.2540

The very marked drop of compressibility on passing from I to III is to be commented on; it is much beyond any possible experimental error. On the other hand, the error is too great to certainly establish any difference in compressibility between III and IV.

Rubber. The measurements were made merely for orienting purposes to provide data for computing the proper size for packing washers intended for use to high pressures. The material was a commercial soft packing, black, and of approximately 1.9 density. Only a single set-up was made, at both temperatures. The results are given in Table XVIII. As is to be expected, this material is highly compressible, much more compressible than any other substance of this paper, although not as compressible as some of the alkali metals. The compression is much greatest at the lowest pressures; the volume decrement between 0 and 5,000 is 17.6 times greater than between 45,000 and 50,000. So large a decrease of compressibility with pressure is characteristic in general of a liquid rather than a solid, and in fact rubber under ordinary conditions is doubtless more like a liquid than a crystalline solid. The unusually large decrease of compression at the lower temperature is also to be noticed.

GENERAL DISCUSSION

Some general remarks should first be made on the accuracy of the results. It is probable that a fairly good idea of the accuracy for any particular material is afforded by the agreement of the results obtained with the different set-ups, but with so many materials there must be some examples of fortuitous unusual combinations of errors. Judged in this way, different materials display a considerable range of probable accuracy. This variation in accuracy is, I believe, not by any means all to be ascribed to the method, but is doubtless in part due to the material. Irregularities to be ascribed to the material might arise from varying chemical purity, from imperfectly defined physical condition, and from excessively high internal friction. Any significant errors arising from imperfect chemical purity are restricted, I believe, to the selenides and tellurides of calcium, strontium, and barium. It is known that some of these are unstable in the air, and BaSe was obviously unstable to severe mechanical handling. Every effort was made to protect these materials as much as possible from the air during the filling of the apparatus, but the difficulty in doing this, and also the fact that different set-ups were made at different intervals of time after the synthesis, makes a certain amount of chemical uncertainty almost inevitable. Error from indefiniteness of physical condition is to be expected chiefly in those substances capable of existing in an amorphous rather than a crystalline condition in the solid. Such a state of affairs is to be expected primarily among those substances which have high melting points and are formed as a fine powder by chemical precipitation. The sulfides of calcium, strontium, and barium preeminently belong here, and also probably PbSe and to a less extent PbTe. In one extreme case, that of MgO, the amorphous effect has been demonstrated[54] to give an apparent compressibility nearly twice too high. The effect is doubtless not so high as this for any of the materials of this paper, but nevertheless I believe it may be quite appreciable for those materials mentioned. To get authentic values of compressibility, massive crystallized material should be used, but in a number of cases this apparently has never been prepared. The amorphous effect appears to play a quite minor role among the halides; these probably recrystallize on compression. With regard to error from excessive internal friction, this may be expected to be high among the brittle materials with high melting point. The effect manifests itself in irregular departures from smooth curves; even the sign of the resulting error is difficult to estimate. In the detailed presentation of data those instances have been specifically mentioned where I believe the effect to be important; ZnSe is perhaps the most striking.

In using the results it should be continually remembered that the measurements are of volume decrement. It is this which is known most accurately, and any derived quantity, such as the compressibility computed from the slope of the curve, must be known less accurately. Furthermore, the measurements are less accurate at the ends of the range; in particular too much significance should not be attached to any large change in the trend of the slopes at the upper end of the range. The shape of the curve of compression is doubtless best in the range from 10,000 to 40,000.

The polymorphic transitions are the most striking phenomena to be considered first in a general discussion. Of the 39 simple compounds investigated here, 15 show transitions below 50,000, not counting the three transitions of the ammonium halides near atmospheric pressure. Of these, six have been previously studied;[10, 16] these are of the rubidium and potassium halides. The volume change of these transitions is large, varying from 8.5 per cent for KI to 14 per cent for RbCl. The viscous resistance to the transition is not particularly high, the latent heat is low, and it is almost certain from theoretical considerations, and from actual experimental demonstration by Jacobs[14] in the case of RbCl, that the high pressure modification has the CsCl structure. The transitions of the three rubidium salts occur at approximately 5,000 kg/cm^2, and those of the three potassium salts at 19,000. Jacobs has had a certain degree of success in discussing these transitions from the quantum mechanical point of view. His calculations suggest that the sodium salts should have no such transition at any pressure, and this agrees with my experimental results up to 50,000, or even nearly 60,000 in some exploratory experiments. These six transitions are similar in having very little change of compressibility on passing through the transition. Another interesting result obvious on plotting the data in the Tables is that the relative volumes (taking as unity the volumes at atmospheric pressure) of the CsCl high pressure modifications at the pressure of transition of the three potassium salts are much more nearly equal than the volumes of the low pressure NaCl modifications below the transition. Of the halides of the other elements, the forms investigated here have the CsCl structure, but NH_4I is known to have NaCl structure at atmospheric pressure at room temperature, and NH_4Cl and NH_4Br have NaCl structures at higher temperatures at atmospheric pressure. The three thallium halides are initially of CsCl structure, and show no change under pressure. Of the silver compounds, AgI is known to have a large transition at about 2,000; Jacobs[15] has found by X-ray analysis that the transition is from the ZnS structure to the NaCl structure. His calculations indicated that, unlike the sodium salts, a further transition to the CsCl structure is to be anticipated at high pressure, but none was found. AgCl and AgBr were previously found to have small sluggish transitions near 25,000. As already mentioned, although possible evidences of them were found in this work, there was nothing very definite, and the results of the Table are smoothed over any possible transition. These two salts are of NaCl structure, so that a transition to the CsCl type is to be looked for. Because of the smallness of the volume change it is hardly probable that the transition suspected in the former experiments, even if it really exists, can be of this type.

Turn now to the transitions of the sulfides, selenides and tellurides. These are all new; furthermore no theoretical calculations appear to have been made for this series of compounds which would suggest either at what pressure transitions might be anticipated or what the structural change is. Among the alkali earth compounds, BaTe alone has a transition, and this at the very top of the pressure range. Since these salts are normally of NaCl structure, a change to CsCl type suggests itself, but if so, the volume change is much smaller than in the other known examples. PbS, PbSe, and PbTe are all normally of NaCl structure, and all have transitions. If this transition is of the KCl type, it differs from that of the potassium and rubidium halides in the smallness of the volume change, and in the considerable variation of the pressure of transition through the series. This occurs at 25,000 for the sulfide and roughly 42,000 for the selenide and telluride, instead of all at the same pressure. Again there is no important change of compressibility on passing through the transition. The zinc compounds are all initially of ZnS (cubic) structure. ZnSe and ZnTe have transitions at 38,000 and 41,000 respectively. The most immediate supposition is that the transition is from the ZnS to the NaCl structure, analogous to the known transition of AgI, but the volume change is an order of ten lower. Again there is no notable change of compressibility on passing through the transition. Finally there are the transitions of the mercury compounds; here qualitatively different phenomena are encountered. HgS ordinarily exists in two forms, a red, hexagonal, and a black, of NaCl structure. The black modification has a 7.5 per cent smaller volume than the red, and has been found in this work to be converted into the red by pressures of 50,000 at room temperature, although it is apparently stable up to 12,000. The initial forms of HgSe and HgTe are of NaCl structure, but these have transitions at pressures of roughly 7,000 and 13,000 with a volume change of the order of 9 per cent. It suggests itself that the change is to the red structure; this, as has already been mentioned, is confirmed by the behavior of the compressibility, which is much greater for the red modification of HgS, and which also increases abnormally on passing from the low to the high pressure modification of HgSe. If the structure of the high pressure modifications is hexagonal, this would be the only example among these substances, the other transitions being from one cubic form to another. Among these cubic forms the order of stability seems to be, from less to greater, ZnS, NaCl, and CsCl. No transition of the latter is known.

Next with regard to the compressions themselves. At 50,000 these range in magnitude from 22 per cent for selenium, and 20 per cent for CsI down to 5 per cent for ZnS (disregarding in this enumeration the effect of transitions). Among the halides of the alkali metals the progression is fairly uniform, the compression increasing as the weight of either the metal or the halogen increases. The same progression also appears at high pressures in the ammonium halides; at low pressures there are irregularities in the relations of the chloride and bromide associated with the different signs in the anomolies of thermal expansion which these exhibit at atmospheric pressure. The thallium halides again show the same progression; the absolute compression of the chloride is about the same as that of NaCl, but the increase on progressing to the iodide is only about one half what it is in the sodium series. The least compressible of the univalent halides investigated here are those of silver; this is to be expected. Their compression is only about one half that of the caesium salts. The compression of AgI above the transition is quite in line with that of the chloride and bromide, if the volume decrement at the transition is subtracted.

The regularities are not so consistent in the series of sulfides, selenides, and tellurides. If one considers the alkali earth series, there is the same increase of compression on passing from the same salt of calcium to strontium to barium that is found in the alkali metal series. But if the alkali earth stays constant and the other element changes, the progression is not so regular. The selenide is always less compressible than the telluride, but the sulfides of calcium and strontium are distinctly more compressible than the corresponding selenide. BaS has initially exactly the same compressibility as BaSe and falls only slightly behind it at the highest pressure. I am inclined to think that these effects are not real, but at any rate in large part are due to excessive compressibility of the sulfide because of an excessive fraction of amorphous material. In the lead series the selenide is out of line, being, below the transition, more compressible than either sulfide or telluride. This effect may be genuine. In the zinc series the progression is normal from sulfide to selenide to telluride, but with an initial close crowding together of selenide and telluride. In the mercury series, comparisons are prevented by the transition. The abnormally high compressibility of the hexagonal modification of HgS has already been commented on.

We next consider the general shape of the curves of volume decrement against pressure. A rough indication of the shape of the curves is given by the ratio of the volume decrement at 50,000 to that at 25,000.[*] If the relation were linear in the pressure, this ratio would be exactly 2; the greater the departure from 2 the greater the curvature and the greater the decrease of compressibility with increasing pressure. These ratios are given in Table XIX for all the materials of this paper for which the calculation is not made impossible by the entrance of a polymorphic transition. If this ratio is plotted against the absolute value of the volume decrement at 25,000, a very definite correlation will be seen, high values of the ratio tending to be associated with small absolute compressions. Or, the smaller the absolute value of compressibility, the smaller the fractional decrease of compressibility for a fixed increase of pressure. This correlation has been

TABLE XIX

Substance	$\Delta V_{50,000} / \Delta V_{25,000}$		Ratio, Calc./Exp.
	Experimental	Calculated	
NaCl	1.640	1.74	1.06
NaBr	1.598	1.71	1.07
NaI	1.510	1.65	1.09
CsCl	1.586	1.69	1.07
CsBr	1.560	1.66	1.06
CsI	1.542	1.62	1.05
NH_4Cl	1.542	1.70	1.10
NH_4Br	1.595	1.675	1.05
NH_4I	1.494	1.64	1.10
AgCl	1.729	1.83	1.06
AgBr	1.794	1.83	1.02
TlCl	1.605	1.73	1.08
TlBr	1.527	1.71	1.02
TlI	1.492	1.68	1.025
CaS	1.502	1.83	1.22
CaSe	1.729	1.85	1.07
CaTe	1.716	1.84	1.07
SrS	1.400	1.80	1.285
SrSe	1.706	1.86	1.09
SrTe	1.656	1.80	1.09
BaS	1.608	1.82	1.13
BaSe	1.654	1.82	1.10
BaTe	1.656	1.79	1.08
ZnS	1.764	1.90	1.08
HgS	1.397	1.75	1.25
In	1.678	1.82	1.08
Sb	1.738	1.81	1.04
S	1.315	1.57	1.19
Se	1.325	1.55	1.17

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[*] This ratio, $\Delta V_{50,000}/\Delta V_{25,000}$, will be abbreviated in what follows as the "50–25 ratio."

known over a smaller pressure range for some time. Another way of exhibiting the same trend is to compare the 50–25 ratio with the ratio calculated by the simple one constant formula of Murnaghan's theory of finite strain.[55] This formula is $p = a(f + 5f^2)$, where $f = \frac{1}{2}\{(V_0/V)^{2/3} - 1\}$. Given $\Delta V_{25,000}$, $f_{25,000}$ may be calculated, and the equation solved for "a." p may then be put equal to 50,000, and the corresponding f and thence $\Delta V_{50,000}$, and finally the 50–25 ratio calculated. These calculated ratios are given in the third column of Table XIX. Murnaghan's one constant formula has the property just discussed, namely that a smaller fractional decrement of compressibility goes with a smaller absolute value of compression, so that in this respect the simple formula reproduces qualitatively the situation, as it was known it must. But if the formula exactly reproduced the facts, the ratio predicted by it should agree with the experimental ratio. The extent to which it satisfies this condition is shown by the fourth column of the table. The ratio of the ratios is without exception high; that is, the compressibility in all cases falls off more rapidly with increasing pressure than is given by Murnaghan's one constant formula. The deficiency varies roughly from 2 to 10 per cent. CaS, SrS, and HgS fall notably out of line. Of these the first two are doubtless due, as shown in the discussion, to deceptive values due to imperfectly crystallized material, while the behavior of HgS is probably to be ascribed to its different crystal system. One might perhaps be inclined to think that the abnormally high compressibility of red HgS could also be due to a high fraction of amorphous material in the original powdered material. This can hardly be the case, however, because the same high compressibility was shown by the red which had been formed by transformation from the black; the mere occurrence of the transition would ensure that under these conditions the bulk of the material is crystalline. The ratio for BaS also falls somewhat out of line, but to a much smaller extent. The unusual shape of the compression of selenium has already been commented on; the discontinuity in $(\partial^2 v/\partial p^2)_T$ at high pressures results in an abnormally low value for the 50–25 ratio.

The fact that the 50–25 ratio is not a function of $\Delta V_{25,000}$ only, but is scattered through a band, means that if all the curves of compression are plotted in a single diagram some crossing will be found. For example, the following pairs cross: CsCl and TlI; NaI and CsBr; BaS and SrS.

The slope of the curve of compression, that is, the compressibility, decreases for most of these substances by from 33 to 50 per cent in the range to 50,000.

The two constant form of Murnaghan's formula, $p = af + bf^2$, would doubtless, with the most advantageous choice of the constants, be capable of representing the experimental results over the entire pressure range. I did not check this in any detail, however. If much more elaborate computations are to be attempted it would probably be more rewarding to use one of the forms of equation given by wave mechanics.

Finally, the temperature effects are to be considered. Warning has already been given that the accuracy of these results is not as great as desirable, and that the results can be used only to establish general trends.

There is one rule to which there are few apparent exceptions, namely that the compressions are less at carbon dioxide temperature than at room temperature. This would be expected intuitively. Furthermore if the differences of compression at these two temperatures are plotted against pressure, the curves in general rise smoothly with pressure, some gently convex and some gently concave toward the pressure axis. Evidently the precise slope of these curves is subject to experimental error. For NH_4Cl, however, the departure of the curve from linearity is so large that it must be beyond experimental error, and is doubtless associated with the known abnormalities at atmospheric pressure near $-40°$, and the variation of these with pressure.

One would like to be able to deduce from the measurements the variation with pressure of the average thermal expansion over the temperature range. This evidently demands a knowledge of the thermal expansion at atmospheric pressure. Unfortunately this seems to be known only for the halides of the alkali metals and ammonium; these data will be found in I.C.T. Even these show irregularities in the progression in a chemical series that make one suspect large inaccuracies in some of the atmospheric data. What one would expect is that at high pressure the natural frequency of atomic vibration would increase because of increased rigidity of the atomic constraints, and that therefore the thermal expansion would decrease. If the calculation is made for the alkali halides (Table XX), it will be found that except in one instance, that of NaI, this expectation is justified. Incidentally there is here a check on the intrinsic probability of the experi-

TABLE XX
EFFECT OF PRESSURE ON THERMAL EXPANSION

Substance	Volume Decrement on Cooling from + 20° C. to −80° C.		Ratio of Column 3 to 2
	At atmos. pressure	At 50,000 kg/cm²	
NaCl	0.0107	.0048	.45
NaBr	.0117	.0092	.79
NaI	.0120	.0130	1.08
KCl*	.0101	.0000	.00
KBr*	.0110	.0012	.11
KI*	.0123	.0038	.31
RbCl*	.0186	.0132	.71
RbBr*	.0110	.0036	.33
RbI*	.0165	.0077	.47
CsCl	.0200	.0118	.59
CsBr	.0140	.0081	.58
CsI	.0146	.0039	.27

* The transition is included in the effect.

mental results; if the compression to 50,000 at the lower temperature as measured here is less than the measured compression at room temperature by an amount greater than the thermal contraction on cooling at atmospheric pressure from room temperature to carbon dioxide temperature, then a negative thermal expansion is demanded at 50,000, a highly improbable result for normal substances. Of the substances above, KCl is the only one which just touches this limitation. A rough average of all the results is that the average expansion at 50,000 is one half that at atmospheric pressure. So large a change means a very considerable change in the effective characteristic temperature. It would appear however, that in general 50,000 kg/cm² is too low a pressure to bring the temperature phenomena normally characteristic of a few degrees above zero absolute up to the temperature of the present measurements.

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THE ELASTIC SCATTERING OF FAST ELECTRONS BY HEAVY ELEMENTS

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Introduction

If, in studying the scattering of fast electrons, one uses foils which are sufficiently thin, then, for all angles above a certain small critical angle,[1] multiple scattering may be supposed to be negligible. Furthermore, the number which is scattered inelastically is small[2] except at very small angles. That is, elastic single scattering is usually of primary importance.

The elastic scattering by light elements has been the subject of theoretical investigation by Mott[3–7] and others, and a general approximate formula has been developed. (Any possible effects due to shielding of the nucleus by the outside electrons have been neglected, i. e. the external electron is pictured as moving in a Coulomb field.) In this formula, it is supposed that $\alpha = (Z/137)$ is small. This is not so for heavy elements, with the result that no simple closed formulae have been found. Mott[8] has derived an exact expression for the scattering of a Dirac electron in a Coulomb field, as a series in Legendre (associated) polynomials. It was the purpose of the present research to sum this series numerically for a typical heavy element (mercury). The results should be approximately true for the nearby elements (gold, lead, thallium, and bismuth).

General Formulae

According to Mott, the intensity of scattering is $ff^* + gg^*$, where

$$\left.\begin{aligned} f &= \tfrac{1}{2}\int_0^\infty y^{-1-iq}\, e^{-y}\, \Phi_b(y)dy \\ g &= \tfrac{1}{2}\int_0^\infty y^{-1-iq}\, e^{-y}\, \Phi_d(y)dy \end{aligned}\right. \qquad (1)$$

$$\Phi_b(y) = i\sum_{k=0}^{\infty}[k(k-iq')c_k y^{\rho_k} + (k+1)(-k-1-iq')c_{k+1}y^{\rho_{k+1}}](-)^k P_k(\cos\theta)$$

$$\Phi_d(y) = i\sum_{k=1}^{\infty}[(k-iq')c_k y^{\rho_k} + (k+iq'+1)c_{k+1}\, y^{\rho_{k+1}}](-)^k P_k^1(\cos\theta)$$

$\rho = (k^2-\alpha^2)^{1/2}$, $q = \alpha/\beta$, $\beta = v/c$, $q' = q(1-\beta^2)^{1/2}$,

and $\qquad c_k = -e^{-i\pi\rho}/\Gamma(\rho + iq + 1)$.

Now abbreviate by letting $S_\rho = \dfrac{e^{-\pi i\rho}}{\rho + iq}\dfrac{\Gamma(\rho - iq)}{\Gamma(\rho + iq)}$,

and note that $\int_0^\infty y^{-1-iq+\rho}e^{-y}\, dy = \Gamma(\rho - iq)$. Also, let $D_k = S_k - S_\rho$. Integrating (1) term by term, we have

$$\left.\begin{aligned} f &= -\tfrac{1}{2}i\sum_{k=0}^{\infty}\{k(k-iq')\,S_{\rho_k} - (k+1)(k+1+iq')\,S_{\rho_{k+1}}\}(-)^k P_k(\cos\theta) \\ &= -iq'F + G \\ \text{and} \\ g &= -\tfrac{1}{2}i\sum_{k=1}^{\infty}\{(k-iq')\,S_{\rho_k} + (k+iq'+1)\,S_{\rho_{k+1}}\}(-)^k P_k^1(\cos\theta) \\ &= -iq'H + K \end{aligned}\right\} \qquad (2)$$

$$F = -\tfrac{1}{2}i\sum[kS_{\rho_k} + (k+1)\,S_{\rho_{k+1}}](-)^k P_k$$

$$G = -\tfrac{1}{2}i\sum[k^2 S_{\rho_k} - (k+1)^2\,S_{\rho_{k+1}}](-)^k P_k$$

$$H = -\tfrac{1}{2}i\sum[S_{\rho_k} - S_{\rho_{k+1}}](-)^k P_k^1$$

$$K = -\tfrac{1}{2}i\sum[kS_{\rho_k} + (k+1)\,S_{\rho_{k+1}}](-)^k P_k^1$$

It will be proved in the Appendix that

$$g = [iq'(1+\cos\theta)F + (1-\cos\theta)G]/\sin\theta \qquad (2a)$$

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[1] See, for instance, W. A. Fowler, Phys. Rev. 54, 773 (1938) for further references.

[2] H. Bethe, Handbuch der Physik, Bd XXIV/1, zw. Aufl, S. 501.

[3] N. F. Mott, Proc. Roy. Soc. (A) 124, 425 (1929).

[4] O. Scherzer, Ann. d. Phys., 13, 137 (1932).

[5] F. Sauter, Z. f. Phys., 86, 818 (1933).

[6] J. Meixner, Z. f. Phys., 90, 312 (1934).

[7] W. H. Furry, Phys. Rev., 46, 391 (1934).

[8] N. F. Mott, Proc. Roy. Soc. (A) 135, 429 (1932). It should be noted that there are misprints in formulae (3.19), (4.2), and (4.4). These formulae are given correctly in the earlier article, ref. (3) above. On page 445, $A' = (e^{3i\beta-(3/2)\pi i}) \times A$, and formula (5.26) should have θ instead of β, while Ψ_c should be similar to Ψ_a. Also, p. 451, $R = (q/2)\{\Gamma(1-iq)/\Gamma(1+iq)\}e^{2iq\log\sin\theta/2}$.

It then follows that

$$ff^* + gg^* = (q'^2 FF^*/\sin^2 \tfrac{1}{2}\theta) + (GG^*/\cos^2 \tfrac{1}{2}\theta) \quad (2b)$$

Mott uses a subscript zero to denote values when $\alpha = 0$. He then sets $F_1 = F - F_0$, and $G_1 = G - G_0$, and obtains

$$\left.\begin{aligned} F_0 &= \frac{i}{2}\left(\sin\frac{\theta}{2}\right)^{2iq} \frac{\Gamma(1-iq)}{\Gamma(1+iq)} = iR/q \\ F_1 &= \tfrac{1}{2} i\,\Sigma[kD_k + (k+1)D_{k+1}]\,(-)^k P_k \\ G_0 &= R\cot^2\frac{\theta}{2} \\ G_1 &= \tfrac{1}{2} i\,\Sigma[k^2 D_k - (k+1)^2 D_{k+1}](-)^k P_k \end{aligned}\right\} \quad (3)$$

We shall show (see Appendix) that

$$k^2 D_k = -(\pi i\alpha^2/2)kS_k + (1/8)[\pi^2\alpha^4 - 4\alpha^2(1+2iq)]\,S_k + E_k \quad (4)$$

where $E_k = O(1/k^2)$ for large k.

Since S_k is of order $(1/k)$, D_k will then be of order $(1/k^2)$. Also, approximately, $kD_k + (k+1)D_{k+1} = -(\pi i\alpha^2/2)(S_k + S_{k+1}) = -(\pi i\alpha^2/2)S_k(2iq+1)/(k+iq+1)$

$$= O(1/k^2).$$

Therefore, F_1 converges rapidly, and need cause no further concern. This is not true of G_1.

$$G_1 = \tfrac{1}{2} i(-\pi i\alpha^2/2)\sum_{k=0}^{\infty}[kS_k - (k+1)S_{k+1}]\,(-)^k P_k + \tfrac{1}{2} i(1/8)\,[\pi^2\alpha^4 - 4\alpha^2(1+2iq)]\sum_{k=0}^{\infty}(S_k - S_{k+1})(-)^k P_k + \tfrac{1}{2} i \sum_{k=0}^{\infty}(E_k - E_{k+1})\,(-)^k P_k = G_1^{\Phi} + G_1^{F_0} + G_1^{E}$$

The first series has been summed by Mott, and a similar procedure may be used for the second series (see Appendix). The third series converges rapidly, so that we need only find the first few terms (numerically).

$$G_1 = [(\pi\alpha^2/4)(1+\cos\theta)\Phi/\Gamma(1+2iq)] + (iF_0/8q)\,[\pi^2\alpha^4 - 4\alpha^2(1+2iq)] + (i/2)\sum(E_k - E_{k+1})\,(-)^k P_k \quad (5)$$

In formula (5)

$$\Phi = \left(2\sin\frac{\theta}{2}\right)^{2iq-2} \int_0^1 \left(\frac{1-z}{z}\right)^{iq} \left(1 + z\cot^2\frac{\theta}{2}\right)^{-\frac{1}{2}} dz$$

Substituting $y = 1 - z$,

$$\Phi = \left(2\sin\frac{\theta}{2}\right)^{2iq-2} \sin\frac{\theta}{2}\int_0^1 \left(\frac{y}{1-y}\right)^{iq} \left(1 - y\cos^2\frac{\theta}{2}\right)^{-\frac{1}{2}} dy$$

$$= \left(2\sin\frac{\theta}{2}\right)^{2iq-2} \sin\frac{\theta}{2}\,\Gamma(iq+1)\,\Gamma(iq-1)\,F\left(\tfrac{1}{2}, iq+1, 2; \cos^2\frac{\theta}{2}\right) \quad (6)$$

where F is the hypergeometric function.[9, 10] The series converges well for $\theta \geq 60°$, but for smaller angles becomes impractical. In this region, it is best to use the connection formula[11]

$$\Gamma\left(\frac{3}{2}\right)\Gamma(-iq+1)\,\Gamma(\tfrac{1}{2})\,\Gamma(iq+1)\,F\left(\tfrac{1}{2}, iq+1, 2; \cos^2\frac{\theta}{2}\right)$$

$$= \Gamma(\tfrac{1}{2})\,\Gamma(iq+1)\,\Gamma(-iq+\tfrac{1}{2})\,F\left(\tfrac{1}{2}, iq+1, iq+\tfrac{1}{2}; \sin^2\frac{\theta}{2}\right) \quad (7)$$

$$+ \Gamma\left(\frac{3}{2}\right)\Gamma(-iq+1)\,\Gamma(iq-\tfrac{1}{2})\left(\sin^2\frac{\theta}{2}\right)^{-iq+\frac{1}{2}} F\left(\frac{3}{2}, -iq+1, -iq+\frac{3}{2}; \sin^2\frac{\theta}{2}\right)$$

SCATTERING AT SMALL ANGLES

At high velocities, $q' \to 0$, and hence the main contribution to the scattering comes from the G term. If we retain only that part of G_1 which has a singularity at $\theta = 0$ (i.e. G_1^{Φ}), then

$$G_1 \cong (\pi\alpha^2/4)\,(1+\cos\theta)\,(2\sin\tfrac{1}{2}\theta)^{2iq-2}\sin\tfrac{1}{2}\theta\,|\Gamma(iq+1)|^2\frac{F_c}{\Gamma(1+2iq)}$$

$$\cong (\pi\alpha^2/8)\sin\tfrac{1}{2}\theta\,(2\sin\tfrac{1}{2}\theta)^{2iq}\,\Gamma(\tfrac{1}{2}-iq)\,\Gamma(1+iq)/\Gamma\left(\frac{3}{2}\right)\Gamma(1+2iq)$$

by substituting (7) and neglecting the second right-hand member.

(We have put $F_c \equiv F(\tfrac{1}{2}, iq+1, 2, \cos^2\tfrac{1}{2}\theta)$.)

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[9] We are deeply indebted to Professor J. R. Oppenheimer for pointing out to one of us (JHB) that this integral is a hypergeometric function. This knowledge saved us considerable labor.

[10] Whittaker and Watson, Modern Analysis, 4th ed., p. 293.

[11] Whittaker and Watson, Modern Analysis, 4th ed., p. 291.

Now the duplication formula for $z = \frac{1}{2} + iq$ is

$$2^{2iq}\,\Gamma(\tfrac{1}{2} + iq)\,\Gamma(1 + iq) = \pi^{1/2}\,\Gamma(1 + 2iq).$$

Using this, we find

$$G \cong \cot^2 \tfrac{1}{2}\theta\,\{-iq\,F_0 + (\pi\alpha^2/4)\,(\sin \tfrac{1}{2}\theta)^{2iq+1}\,[\Gamma(\tfrac{1}{2} - iq)/\Gamma(\tfrac{1}{2} + iq)]\}$$

which could be written in the form

$$G \cong e^{i\psi} \cot^2 \tfrac{1}{2}\theta\,\{(q/2) + (\pi\alpha^2/4) \sin \tfrac{1}{2}\theta\, e^{i\chi}\}$$

where χ and ψ are real angles and

$$e^{i\chi} = \Gamma(\tfrac{1}{2} - iq)\,\Gamma(1 + iq)\,/\,\Gamma(\tfrac{1}{2} + iq)\,\Gamma(1 - iq)$$

Then, $$GG^* \cong \cot^4 \tfrac{1}{2}\theta[(q^2/4) + (\pi\alpha^2 q/4) \sin \tfrac{1}{2}\theta \cos \chi] \quad (8)$$

For $\alpha = 0$, and $q' = 0$ ($v = c$), this reduces[12] to Mott's formula (ref. 8, eq. 6.9). If q is small with respect to $\frac{1}{2}$, then χ is small, and $\cos \chi \cong 1$. We then have the improved formula already given by Mott (ref. 3, p. 438, equation before (25)). However, as Mott himself has remarked, this formula does not hold for gold (since $q_{min} = .58$) and the polarization effects cannot be calculated at all satisfactorily until we take in more terms. Any correction occasioned by the inclusion of $\cos \chi$ will reduce the value of the scattering below that found by Mott. For $q = .6$, we find $\chi = 1.10722$, and $\cos \chi = .44715$. Substituting in (8), we find that the scattering is not very different, at angles less than 15°, from that calculated with the exact formula. The deviations at larger angles are, of course, to be expected. (See Fig. 1 for the comparison.)

POLARIZATION

According to Mott, the asymmetry to be expected in a double scattering (90°) experiment is measured by $2\delta = 2[(fg^* - gf^*)/(ff^* + gg^*)]^2$. Let $F = a + ib$, and $G = c + id$. Then $FG^* + GF^* = 2(ac + bd)$. $fg^* - gf^* = -iq'\,(\cot \frac{1}{2}\theta + \tan \frac{1}{2}\theta)\,(FG^* + GF^*) = -4iq'\,(ac + bd)/\sin \theta = -4iq'\,(ac + bd)$ for angles of 90°. The polarization thus goes to zero as $v \to c$, because $q' \to 0$.

CALCULATION PROCEDURE

In order to find F_1 and G_1, one needs to know S_k, S_ρ, and the derived quantities D_k and E_k, as well as the hypergeometric functions in (6) and (7). The latter may be calculated simply by summing the series, while the former depend upon gamma functions of a complex argument.[13] We may note that the phases only of these gamma functions are needed for S_k and S_ρ. It is probably most accurate to make all the primary calculations of phases in the region where the asymptotic formula holds, and to extend inwards by repeatedly applying the formula $z\Gamma(z) = \Gamma(z + 1)$. For large z, we have $\ln \Gamma(z) \sim (z - \frac{1}{2}) \ln z - z + \frac{1}{2} \ln 2\pi + (1/12\,z) - (1/360\,z^3) + \ldots\ldots$ Let $z = re^{i\theta} = a + ib$, and $\Gamma(z) = Re^{i\psi}$. Then $\ln R + i\psi \sim (a + ib - \frac{1}{2})\,(\ln r + i\theta) - a - ib + \frac{1}{2} \ln 2\pi + (a - ib)/(12r^2) - (a^3 - 3a^2bi - 3ab^2 + ib^3)/360r^6 + \ldots\ldots$. Equating imaginary parts,

$$\psi \sim (a - \tfrac{1}{2})\,\theta + b\,(\ln r - 1) - (b/12r^2) + (3a^2b - b^3)/(360r^6) + \ldots\ldots \quad (9)$$

If $b^2 << 3a^2$, then

$$\psi \sim (a - \tfrac{1}{2})\theta + b\,(\ln r - 1) - (b/12r^2) + (b/120r^4) + \ldots\ldots \quad (10)$$

Formula (10) is simpler to apply in most cases, but we have used formula (9) for $q \geq 1.5$ ($a = 5$ and 6). The calculation of S_ρ is made most conveniently in the polar co-ordinate system, where one needs only to add angles.

Once we have D_k, we may find E_k from formula (4), and then G_1 from (5). F_0, F_1, and G_0 are obtained by using formula (3), and the calculation of scattering intensity is completed with an application of (2b).

In spite of the complexity of our calculations, we are confident of their correctness for the following reasons: (1) They have been made in duplicate, i. e. by two men working independently, so that local errors have been eliminated; (2) Our results on polarization check with those of Mott as closely as would be expected, so that there are no systematic errors at 90°; and (3) our values of r at other angles are consistent with those at 90°, and give a family of curves varying smoothly with q.

RESULTS

It is convenient to tabulate the ratio r of our calculated scattering intensity to ordinary Rutherford scattering. That is, we multiply our values by $(4/q^2) \sin^4 \frac{1}{2}\theta$. In Table I, we list the values of the ratio r, together with those of δ (polarization), as a function of q or of ε ($= E/mc^2$).

In Figure 1, we have plotted (1) our exact values of r for all our values of q, (2) the values of r for $q = 0.6$ on the basis of our formula (8),

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[12] One must, of course, use formula (2b) of this paper in making the comparison.

[13] The functions of an imaginary argument (modulus ≤ 1) have been tabulated by H. T. Davis, Tables of the Higher Mathematical Functions, vol. I, p. 272. An excellent idea of the general behavior of the functions of a complex argument may be gained by looking at the graph of Jahnke-Emde, Funktionentafeln, (1933), S. 90.

TABLE I

VALUES OF r AND δ

q	ϵ	15°	30°	45°	60°	90°	120°	150°	180°	δ
.6	3.35	1.12	1.34	1.62	1.85	1.89	1.30	.51	.15	.012
.65	1.28	1.09	1.29	1.55	1.78	1.89	1.44	.82	.54	.036
.73	.666	1.06	1.22	1.45	1.67	1.86	1.59	1.19	1.00	.057
.8	.463	1.04	1.17	1.37	1.58	1.82	1.68	1.43	1.31	.064
.9	.314	1.03	1.11	1.28	1.48	1.77	1.75	1.65	1.59	.068
1.0	.232	1.02	1.07	1.21	1.39	1.71	1.78	1.80	1.78	.066
1.2	.145	1.01	1.02	1.09	1.25	1.58	1.79	1.97	1.98	.057
1.5	.086					1.39	1.73	2.05	2.31	
2.0	.046					1.19	1.58	2.04	2.35	.027

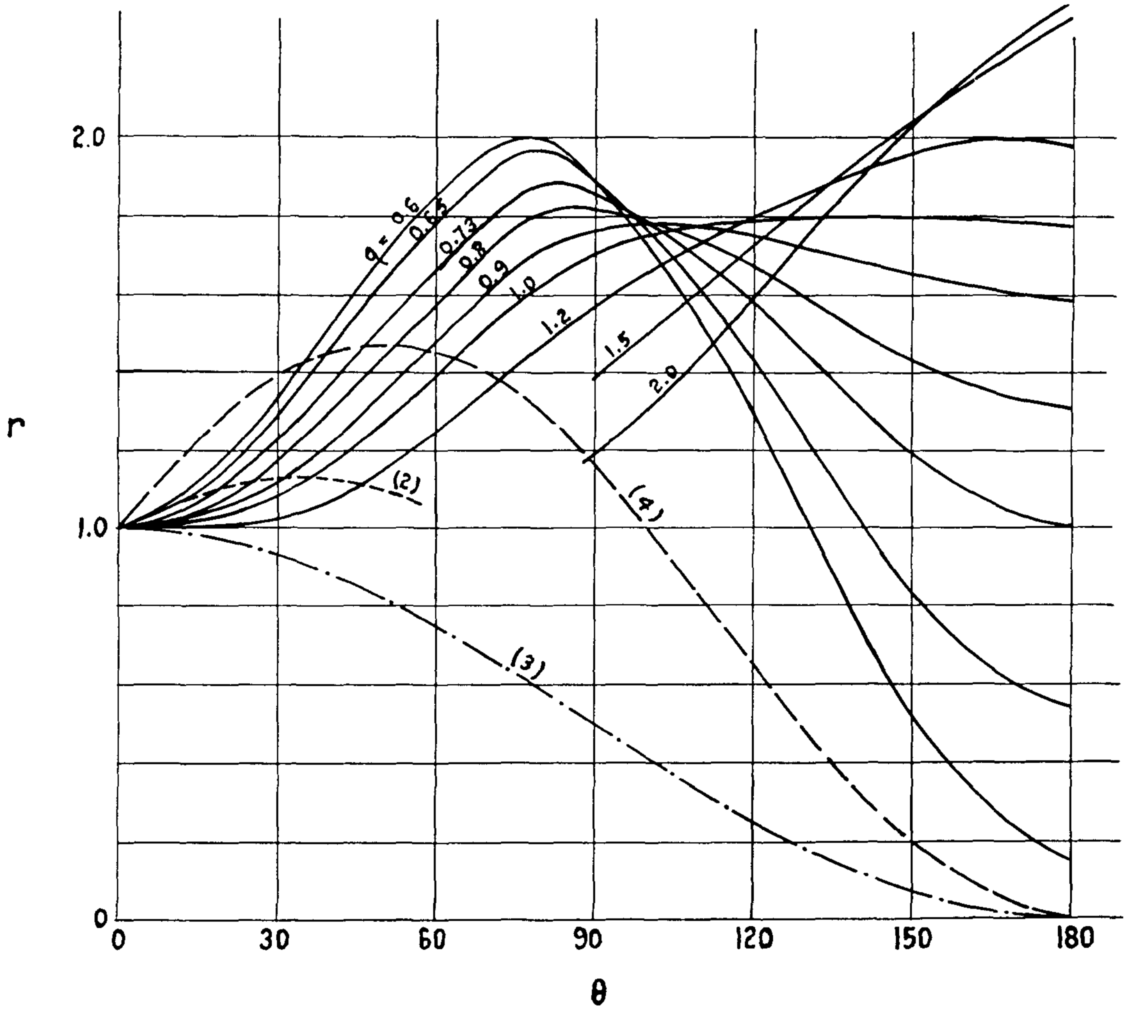

FIGURE 1. $\frac{\text{Calculated scattering}}{\text{“Rutherford” scattering}}$ vs. Angle.

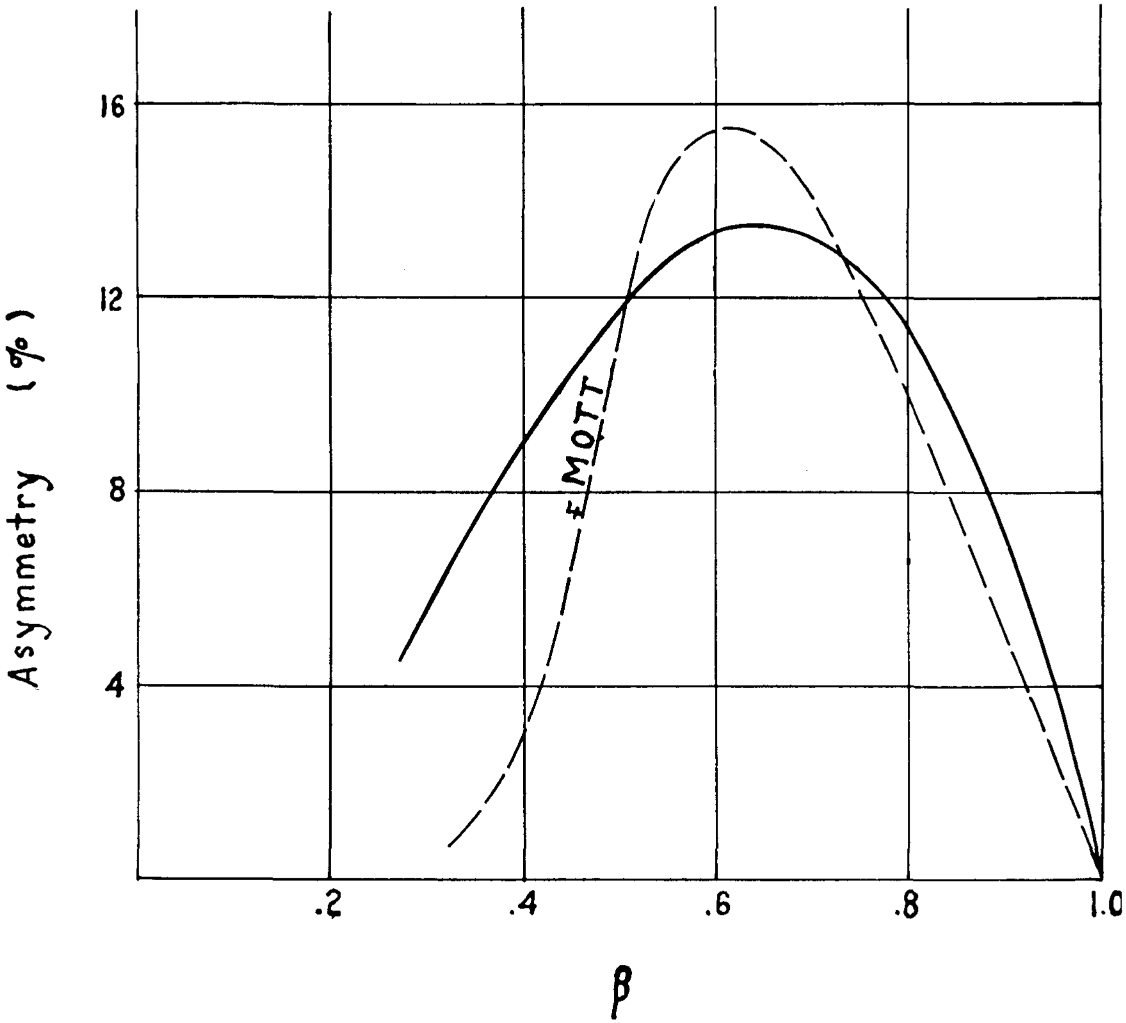

Figure 2. Asymmetry per 100 electrons vs. velocity.

(3) the values of r found from Mott's light element formula with neglect of α^2, and (4) the same for Hg with inclusion of α^2. As previoulsy remarked, (4) cannot be used legitimately for heavy elements. The difference between (1) and (3) is great, and may be thought of as due to the spin-orbit interaction. Just how this interaction enters is not immediately obvious, but a detailed analysis of our results might possibly lead to an interpretation in terms of a model.

In Figure 2, we have plotted 2δ, and show Mott's results for comparison. It is seen that our polarization values are only slightly less than his at the maximum.

Since the scattering is approximately Rutherford at small angles, we can offer no explanation of the results of Fowler and Oppenheimer[1] on multiple scattering. Our angular distribution agrees well with that observed by Barber and Champion,[14] the numbers in the angular ranges 20°–30°, 30°–60°, and 60°–180° being in the ratio 37 : 27 : 9, as against the experimental ratio 37 : 30 : 8. However, the disagreement between theory and experiment with respect to absolute intensities[14] still remains.

Acknowledgments

We are grateful to Professor J. R. Oppenheimer not only for the specific help referred to in footnote 9, but also for illuminating discussion of the subject in general. Furthermore, it would not have been possible to carry out this work as

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[14] A. Barber and F. C. Champion, Proc. Roy. Soc. A 168, 159 (1938).

completely as here presented, had it not been for the computational assistance rendered available (1) by a grant from the Graduate School and (2) by Professor F. W. Loomis. We wish to thank the men who aided in the computations, Messrs. F. N. Gillette, R. W. Potts (NYA), and P. R. Gillette, for their capable and efficient work.

APPENDIX

I. *Derivation of Equation (4)*

Expand S_ρ in a Taylor's series, as follows:

$$S_\rho = S_k + \left.\frac{dS_\rho}{d\rho}\right|_k (\rho - k) + \left.\frac{d^2S_\rho}{d\rho^2}\right|_k \frac{(\rho-k)^2}{2} + \ldots \quad \text{(A1)}$$

$$\rho = k\left(1 - \frac{\alpha^2}{k^2}\right)^{1/2} = k\left\{1 - \frac{\alpha^2}{2k^2} + \frac{3}{8}\frac{\alpha^4}{k^4}\ldots\ldots\right\} \quad \text{(A2)}$$

We shall consistently neglect terms of order (S_k/k^3), or of order $(1/k^4)$. Denote $\frac{d}{dz}\log\Gamma(z)$ by $\psi(z)$. Since $\log S_\rho = -\pi i\rho + \log\Gamma(\rho - iq) - \log\Gamma(\rho + iq + 1)$, we have on differentiating:

$$\frac{1}{S_\rho}\frac{dS_\rho}{d\rho} = -\pi i + \psi(\rho - iq) - \psi(\rho + iq + 1)$$

$$\frac{1}{S_\rho}\frac{d^2S_\rho}{d\rho^2} - \frac{1}{S_\rho^2}\left(\frac{dS_\rho}{d\rho}\right)^2 = \psi'(\rho - iq) - \psi'(\rho + iq + 1)$$

The $(1/k^3)$ term in $\rho - k$ may be neglected, so that the terms contributing to $(dS_\rho/d\rho)_k$ will be of order S_k and (S_k/k), respectively. Likewise, contributions to $(d^2S_\rho/d\rho^2)_k$ will come only from terms of order S_k. Now, for large k,[15]

$$\psi(k + iq) \sim \tfrac{1}{2}\log(k^2 + q^2) + i\tan^{-1}(q/k) - [\tfrac{1}{2}(k + iq)]\ldots$$

$$\psi(k - iq) \sim \tfrac{1}{2}\log(k^2 + q^2) - i\tan^{-1}(q/k) - [\tfrac{1}{2}(k - iq)]\ldots$$

$$\psi(k - iq) - \psi(k + iq) \sim -2i\tan^{-1}(q/k) \cong -2iq/k \text{ if } q << k$$

$$\psi(k + iq) - \psi(k + iq + 1) = -1/(k+iq)$$

Hence $\left.\dfrac{dS_\rho}{d\rho}\right|_k \cong S_k[-\pi i - [(1 + 2iq)/k]]$

and $\left.\dfrac{d^2S_\rho}{d\rho^2}\right|_k \cong -S_k\pi^2$

Substituting in (A1), using (A2),

$$k^2D_k \cong -(\pi i\alpha^2/2)\,kS_k + (1/8)\,[\pi^2\alpha^4 - 4\alpha^2(1 + 2iq)]\,S_k \quad (4)$$

II. *Proof of Equation (2a)*

This equation will be correct,[16] if we can show that

$$H = -(1+\cos\theta)F/\sin\theta \quad \text{(A3)}$$

$$K = (1-\cos\theta)G/\sin\theta \quad \text{(A4)}$$

(a) *Proof of (A3)*

Since $g = 0$ for the non-relativity case ($\alpha = 0$ and $q = q'$), we have $K_0 = iqH_0$. In general, $K = \sin\theta\,\{d/d(\cos\theta)\}F$. If we apply this to F_0, we have $K_0 = \sin\theta\, f(q)\,(d/d\cos\theta)\,(1 - \cos\theta)^{iq} = -\sin\theta\, f(q)iq(1 - \cos\theta)^{iq-1} = -iq\,\{\sin\theta/(1 - \cos\theta)\}F_0$. Accordingly, $H_0 = -[\sin\theta/(1-\cos\theta)]F_0$. Can we now show that $H_1 = -[\sin\theta/(1-\cos\theta)]F_1$?

$$H_1 = (i/2)\sum_{k=1}^{\infty}(D_k - D_{k+1})\,(-)^kP_k^1$$

$$= (i/2)\sum_{k=1}^{N}(D_k - D_{k+1})\,(-)^kP_k^1 + \left(\frac{i}{2}\right)\sum_{N+1}^{\infty}(D_k - D_{k+1})\,(-)^kP_k^1$$

Now, $D_k - D_{k+1} \cong -(\pi i\alpha^2/2)\,[(S_k/k) - [S_{k+1}/(k+1)]] = O\,(1/k^2)$.

Since the terms are of this order, the sum will be of order $(1/N)$ and may be neglected.

$$H_1 \cong (i/2)\,[-D_1(P_1^1 + P_2^1) + \ldots\ldots + D_N(-)^N(P_{N-1}^1 + P_N^1) - D_{N+1}(-)^NP_N^1]$$

$$\cong (i/2)\sum_{k=1}^{N}(-)^kD_k\,(P_{k-1}^1 + P_k^1)$$

But $P_k^1 + P_{k-1}^1 = k(P_{k-1} - P_k)\,(1 + \cos\theta)/\sin\theta$

$P_k^1 - P_{k-1}^1 = k(P_{k-1} + P_k)\,(1 - \cos\theta)/\sin\theta$

$$\text{Hence } H_1 \cong (i/2)\left[\sum_{k=1}^{N}(-)^k D_kk\,(P_{k-1} - P_k)\right](1 + \cos\theta)/\sin\theta$$

$$\cong (i/2)\,[(1 + \cos\theta)/\sin\theta]\,\{-D_1(P_0 - P_1) + 2D_2(P_1 - P_2) + \ldots.(-)^N ND_N(P_{N-1} - P_N)\}$$

$$\cong -(i/2)\,[(1+\cos\theta)/\sin\theta]\,\{D_1P_0 - P_1(D_1 + 2D_2) \ldots\ldots + (-)^{N-1}P_{N-1}[(N-1)D_{N-1} - ND_N]\} - (i/2)\,[(1 + \cos\theta)/\sin\theta]\,(-)^{N+1}P_NND_N$$

$$\cong -(i/2)\,[(1 + \cos\theta)/\sin\theta]\sum_{k=0}^{N-1}\{kD_k + (k+1)D_{k+1}\}\,(-)^kP_k$$

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[15] H. T. Davis, Tables of the Higher Mathematical Functions, vol. 1, p. 283.

[16] We have also calculated g directly, i. e., from equation (2), and have obtained approximately the same results as with equation (2a). The approximative character of these results arises from the neglect of series terms with $k \geq 4$.

But $F_1 = (i/2)\sum_{k=0}^{N-1}\{kD_k + (k+1)D_{k+1}\}(-)^k P_k +$

$$(i/2)\sum_{N}^{\infty}\{kD_k + (k+1)D_{k+1}\}(-)^k P_k$$

$kD_k + (k+1)D_{k+1} \cong -(\pi i\alpha^2/2)[S_k + S_{k+1}] = O(1/k^2)$, so that the sum of these terms may be neglected.

Therefore $H_1 = -[(1+\cos\theta)/\sin\theta]F_1$, which proves equation (A3).

(b) *Proof of (A4).*

$$K_0 = [-iq\sin\theta/(1-\cos\theta)]F_0 = -iq\cot\frac{\theta}{2}F_0$$

$$G_0 = -iq\cot^2\frac{\theta}{2}F_0 = \cot\frac{\theta}{2}K_0 = [\sin\theta/(1-\cos\theta)]K_0 \qquad \text{(A5)}$$

Can we show that $K_1 = G_1\tan(\theta/2)$?

$$K_1 = \tfrac{1}{2}i\sum_{k=1}^{\infty}[kD_k + (k+1)D_{k+1}](-)^k P_k^1$$

$$= -\tfrac{1}{2}i(\pi i\alpha^2/2)\sum_{k=1}^{\infty}[S_k + S_{k+1}](-)^k P_k^1$$

$$+\tfrac{1}{2}i(1/8)[\pi^2\alpha^4 - 4\alpha^2(1+2iq)]\sum_{k=1}^{\infty}\left(\frac{S_k}{k}+\frac{S_{k+1}}{k+1}\right)(-)^k P_k^1$$

$$+\tfrac{1}{2}i\sum_{k=1}^{\infty}\left[\frac{E_k}{k}+\frac{E_{k+1}}{(k+1)}\right](-)^k P_k^1 = K_1' + K_1'' + K_1'''$$

The first term is found to be (see Appendix IIc)

$$K_1' = (\pi\alpha^2/4)\,\Phi\sin\theta/\Gamma(1+2iq) \qquad \text{(A6)}$$

There is a corresponding term in G_1, namely

$$G_1^{\Phi} = (\pi\alpha^2/4)(1+\cos\theta)\Phi/\Gamma(1+2iq) = K_1'\cot\frac{\theta}{2} \qquad \text{(A7)}$$

Now, the coefficients of P_k^1 in $K_1'' + K_1'''$ are of order $(1/k^2)$, and so we may make the same transformation as in IIa.

$$K_1'' + K_1''' = \tfrac{1}{2}i\sum_{k=1}^{\infty}(H_k + H_{k+1})(-)^k P_k^1$$

$$= \tfrac{1}{2}i\sum_{k=0}^{\infty}[kH_k - (k+1)H_{k+1}](-)^k P_k \,(1-\cos\theta)/\sin\theta$$

$$= [(1-\cos\theta)/\sin\theta](G_1^{F_0} + G_1^{E}) \qquad \text{(A8)}$$

Combining (A5), (A7), and (A8), we have (A4). It should be noticed that the transformation is not made on the series K_1 itself, for the term N^2D_N is not negligible.

(c) *Derivation of (A6)*[17]

$$\sum_{k=1}^{\infty}[S_k + S_{k+1}](-)^k P_k^1 = [1/\Gamma(1+2iq)]\int_0^1 (1-x)^{2iq}x^{-iq-1}\sum_{k=1}^{\infty}(x^k - x^{k+1})P_k^1\,dx$$

$$= [1/\Gamma(1+2iq)]\sin\theta\int_0^1\left(\frac{1-x}{x^{1/2}}\right)^{2iq}\left(\frac{1-x}{x}\right)\frac{d}{d\mu}\sum_{k=0}^{\infty}x^k P_k\,dx$$

$$= [1/\Gamma(1+2iq)]\sin\theta\int_0^1\left(\frac{1-x}{x^{1/2}}\right)^{2iq}(1-x)(1-2x+x^2)^{-3/2}dx$$

$$= \Phi\sin\theta/\Gamma(1+2iq)$$

III *Evaluation of $G_1^{F_0}$*

$$\sum_{k=0}^{\infty}(S_k - S_{k+1})(-)^k P_k$$

$$= [1/\Gamma(1+2iq)]\int_0^{\infty}(1-x)^{2iq}x^{-iq}(1+x)\sum_{k=0}^{\infty}x^{k-1}P_k\,dx$$

$$= [1/\Gamma(1+2iq)]\int_0^{\infty}(1-x)^{2iq-1}x^{-iq}dx[(1-x^2)(1-2\mu x+x^2)^{-1/2}/x]$$

$$= [1/\Gamma(1+2iq)]\int_0^{\infty}(1-x)^{2iq-1}x^{-iq}dx\int^{\mu}\mathrm{F}(x,\mu)d\mu$$

$$= [2i\Gamma(2iq)/\Gamma(1+2iq)]\int^{\mu}f(\mu)d\mu = (1/q)\int^{\mu}f(\mu)d\mu,$$

where $f(\mu)$ and $F(x,\mu)$ are the functions used by Mott in Appendix II, ref. 8. Mott finds $f(\mu) = (q/2)[\Gamma(1-iq)/\Gamma(1+iq)][(1-\mu)/2]^{iq-1}$. Therefore, $\int^{\mu}f(\mu)d\mu = f(\mu)[(1-\mu)/2][2i/q] = 2iR/q = 2F_0$. Hence, the above sum equals $2F_0/q$, which leads immediately to $G_1^{F_0}$ (see equation (5)).

ABSTRACT

Exact formulae for the scattering of Dirac electrons by a Coulomb field have been developed by Mott.[8] We have used these to calculate the angular distribution of the scattering of fast electrons in mercury, a typical heavy element. Curves are given for energies of 23 kv and upwards. Above 2 MEV, the angular distribution has an asymptotic character. It is of Rutherford type for very small angles, but the scattering at 60° is about twice as large as Rutherford scattering. The polarization has also been calculated, and is approximately the same as found by Mott.[8]

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[17] See N. F. Mott, Proc. Roy. Soc. A 135, 456 (1932), Appendix I.

TABLE II

		$q = .6$	.65	.73	.8	.9	1.0	1.2	1.5	2.0
Phase of $\Gamma(\rho+iq)$	$\rho = 0.8117957$	−25° 21′ 29″	−26° 28′ 05″	−27° 53′ 31″	−28° 47′ 53″	−29° 33′ 47″	−29° 44′ 54″	−28° 32′ 27″	−23° 19′ 11″	− 7° 18′ 24″
	1.9128545	13 26 21	14 43 09	16 50 33	18 46 49	21 41 19	24 46 20	31 29 33	43 1 34	66 11 43
	2.9426200	31 15 41	33 55 40	38 13 15	42 0 45	47 29 06	53 01 52	64 22 11	82 3 53	113 38 22
	3.9571470	42 55 45	46 32 15	52 19 39	57 24 36	64 42 05	72 02 06	86 49 53	109 24 53	148 16 39
	4.9657841								130 20 4	175 17 53
Phase of $\Gamma(k+iq)$	$k = 1$	−15 37 38	−16 15 52	−17 01 33	−17 25 51	−17 35 39	−17 16 58	−15 18 59	− 9 20 9	7 25 42
	2		16 45 34					34 52 41	46 58 27	70 51 47
	3		34 45 49					65 50 31	83 50 39	115 51 47
	4		46 59 19					87 38 36	110 24 33	149 33 12
	5		56 13 07					104 20 33	130 57 55	176 7 6

TABLE III (A)

		q = .6		.65		.73		.8	
		R	I	R	I	R	I	R	I
	ρ = 0.8117957	− .661257	− .737616	− .641815	− .716033	− .616503	− .677422	− .599587	− .640552
	1.9128545	.437922	− .238834	.417370	− .266101	.380126	− .306680	.343585	− .338469
S_ρ	2.9426200	− .147435	.298563	− .113585	.311789	− .057015	.324870	− .006262	.327871
	3.957147	.014093	− .249454	− .020387	− .248531	− .074289	− .237151	− .118326	− .217606
	4.9657841					.122447	.157169		
	k = 0	− .864726	1.424790	− .827269	1.297108	− .767042	1.134977	− .714496	1.025668
	1	− .857482	− .004346	− .838412	.007243	− .807156	.029284	− .779154	.051726
	2	.324334	− .352372	.295867	− .372262	.247093	− .399443	.201618	− .418172
S_k	3	− .082492	.316279	− .046733	.322405	.011228	.323688	.061610	.317191
	4	− .022504	− .246208	− .056379	− .240236	− .107837	− .221035	− .148329	− .195179
	5								
	k = 0	− .314891	− .138379	− .309870	− .148273	− .303267	− .160234	− .299118	− .167165
	1	− .216201	.098431	− .224760	.088572	− .235459	.074248	− .242457	.063800
	2	.003989	− .049883	.003285	− .052190	+ .001880	− .055650	− .000375	− .059139
E_k	3	.009326	.018572	.010878	.018813	.013799	.018952	.016307	.028268
	4	− .008299	− .007541	− .009453	− .007071	− .011107	− .006016	− .012648	− .004694
	5								

TABLE III (B)

.9		1.0		1.2		1.5		2.0	
R	I	R	I	R	I	R	I	R	I
− .582867	− .583947	− .572931	− .523943	− .565150	− .396262	− .554573	− .190285	− .436939	+ .154021
.285418	− .377227	.221361	− .406985	.081463	− .435295	− .130319	− .390192	− .345513	− .105764
.065610	.318281	.133449	.292783	.243148	.199747	+ .302736	− .004287	+ .090794	− .265992
− .172721	− .175749	− .213323	− .120503	− .241540	.011894	− .145885	+ .185890	+ .161289	+ .157648
						− .004433	− .192724	− .185642	+ .020740
− .640292	.908072	− .567349	.823478	− .424609	.717043	− .213428	+ .631580	+ .128199	+ .483286
− .738067	.087998	− .695413	.128064	− .603234	.214349	− .439256	+ .338743	− .090755	+ .437908
.133203	− .436070	.062158	− .442873	− .079751	− .421264	− .261465	− .302715	− .351120	+ .041411
.129561	.291806	.190357	.252516	.276939	.138167	+ .288965	− .073405	+ .022164	− .276463
− .195608	− .145691	− .227149	− .085010	− .234236	.049728	− .112145	+ .205470	+ .184659	+ .126101
						− .028744	− .189397	− .180150	+ .045043
− .295996	− .171937	− .296142	− .171185	− .304888	− .154350	− .328814	− .092081	− .326121	.100501
− .249303	.052495	− .253554	.045865	− .256918	.046468	− .251263	.078243	− .189467	.185228
− .004295	− .063598	− .009690	− .067749	− .023362	− .073336	− .052541	− .072104	− .104528	− .025771
.020617	.017562	.025459	.015216	.033066	.007836	.039373	− .011917	.015712	− .050990
− .014627	− .002140	− .016248	.001463	− .016372	.008983	− .008505	.021199	.022737	.020200
						− .004457	− .013611	− .018917	.003477

TABLE IV (A)

	q = .6		.65		.73		.8	
	M	Φ	M	Φ	M	Φ	M	Φ
$\Gamma(iq+1)$	.765451	−.272744	.734196	−.283868	.683876	−.297157	.640197	−.304226
$\Gamma(iq+\frac{1}{2})$	.965668	−.826353	.895450	−.856438	.792304	−.895082	.711081	−.920275
$\Gamma(iq-\frac{1}{2})$	1.236411	−3.191298	1.105411	−3.082928	.895445	−3.066419	.753745	−3.049671

(M is modulus—Φ is phase)

TABLE IV (B)

.9		1.0		1.2		1.5		2.0	
M	Φ	M	Φ	M	Φ	M	Φ	M	Φ
.579433	−.307074	.521564	−.301641	.417033	−.267320	.290985	−.162940	.153190	.129647
.608642	−.944008	.520591	−.955008	.380495	−.944631	.237569	−.863152	.108321	−.592538
.591165	−3.021903	.465631	−2.989452	.292688	−2.910218				

TABLE V (A)

		$\theta = 15°$		30°		45°		60°	
Phase of $(\sin \frac{1}{2}\theta)^{-2iq}$	q = .6		2.443417		1.621951		1.152659		.831777
	.65		2.647036		1.757114		1.248711		.901091
	.73		2.972825		1.973374		1.402399		1.011995
	.8		3.257890		2.162602		1.536875		1.109036
	.9		3.665126		2.432927		1.728985		1.247665
	1.0		4.072363		2.703252		1.921094		1.386294
	1.2		4.886835		3.243903		2.305313		1.663553
	1.5								
	2.0								
		R	I	R	I	R	I	R	I
$2F_0/i$	q = .6	−.321329	−.946968	.474445	−.880285	.821267	−.570544	.959299	−.282394
	.65	−.486870	−.873474	.372237	−.928138	.776959	−.629551	.944950	−.327215
	.73	−.722709	−.691143	.190563	−.981675	.690884	−.722965	.914032	−.405642
	.8	−.881317	−.472525	.016645	−.999861	.599097	−.800677	.877302	−.479939
	.9	−.995897	−.090491	−.245448	−.969410	.440325	−.897839	.805951	−.591983
	1.0	−.946854	.321664	−.504820	−.863225	.250295	−.968170	.708793	−.705417
	1.2	−.352457	.935828	−.907992	−.418988	−.198547	−.980091	.427643	−.903948
	1.5								
	2.0								
$2F_1/i$	q = .6	.1446	.0346	.1345	.1647	.1036	.3435	.0407	.5308
	.65	.1443	.0151	.1392	.1468	.1136	.3283	.0532	.5188
	.73	.1386	−.0157	.1436	.1173	.1294	.3016	.0762	.4963
	.8	.1286	−.0410	.1444	.0924	.1428	.2778	.0987	.4750
	.9	.1068	−.0735	.1399	.0554	.1593	.2379	.1325	.4373
	1.0	.0777	−.0987	.1295	.0222	.1727	.1973	.1669	.3952
	1.2	.0062	−.1203	.0935	−.0295	.1846	.1139	.2269	.2962
	1.5								
	2.0								

TABLE V (B)

90°		120°		150°		180°	
	.415888		.172609		.041602		
	.450546		.186993		.045069		
	.505997		.210008		.050616		
	.554518		.230146		.055469		
	.623833		.258914		.062403		
	.693147		.287682		.069336		
	.831777		.345219		.083204		
	1.039721		.431523		.104005		
	1.386294		.575364		.138673		
R	I	R	I	R	I	R	. I
.991614	.129237	.931282	.364298	.875713	.482832	.854874	.518836
.993141	.116923	.928389	.371610	.866491	.499193	.843119	.537726
.996103	.088201	.927059	.374916	.855803	.517302	.828533	.559940
.998546	.053907	.929292	.369346	.850962	.525227	.820535	.571597
.999953	— .009684	.937565	.347810	.851611	.524175	.817265	.576261
.995965	— .089744	.950610	.310388	.860805	.508935	.823478	.567349
.956179	— .292782	.982113	.188292	.899821	.436260	.860452	.509531
.755852	— .654762	.994425	— .105448	.975487	.220059	.947370	.320142
— .074722	— .997204	.671431	— .741067	.921851	— .387545	.966571	— .256398
— .1800	.8202	— .4250	.9791	— .5673	1.0844	— .6035	1.1316
— .1753	.8135	— .4358	.9728	— .5854	1.0740	— .6220	1.1187
— .1599	.8012	— .4422	.9642	— .6016	1.0596	— .6381	1.0997
— .1394	.7880	— .4378	.9574	— .6040	1.0528	— .6397	1.0913
— .0989	.7705	— .4148	.9558	— .5910	1.0420	— .6271	1.0698
— .0486	.7482	— .3749	.9569	— .5591	1.0410	— .5956	1.0608
.0724	.6889	— .2478	.9641	— .4460	1.0549	— .4890	1.0591
.2721	.5808	.0349	.9140	— .1709	1.0787	— .2282	1.1665
.5000	.1506	.5550	.6104	.4669	.8976	.4725	.9627

TABLE VI

		$\theta = 15^\circ$		30°		45°		60°	
		R	I	R	I	R	I	R	I
$F(\frac{1}{2}, iq+1, iq+\frac{1}{2}; \sin^2 \frac{1}{2}\theta)$	$q =$ .6	1.01220	− .00428	1.05037	− .01791	1.11971	− .04358		
	.65	1.01187	− .00420	1.04900	− .01761	1.11636	− .04288	1.22389	− .08540
	.73	1.01142	− .00406	1.04709	− .01700	1.11171	− .04143	1.21417	− .08234
	.8	1.01108	− .00391	1.04569	− .01640	1.10831	− .04001	1.20787	− .07988
	.9	1.01069	− .00370	1.04405	− .01551	1.10430	− .03787	1.19986	− .07575
	1.0	1.01038	− .00348	1.04274	− .01463	1.10109	− .03576	1.19343	− .07165
	1.2	1.00993	− .00309	1.04083	− .01301	1.09640	− .03188	1.18398	− .06408
		$\theta = 15^\circ$		30°		45°		60°	
		R	I	R	I	R	I	R	I
$F(3/2, -iq+1, -iq+3/2; \sin^2 \frac{1}{2}\theta)$	$q =$ .6	1.01853	− .00301	1.07675	− .01269	1.18350	− .03128		
	.65	1.01870	− .00318	1.07750	− .01344	1.18527	− .03315	1.35978	− .06724
	.73	1.01899	− .00343	1.07871	− .01451	1.18816	− .03585	1.3646	− .07256
	.8	1.01925	− .00362	1.07980	− .01533	1.19082	− .03794	1.37073	− .07725
	.9	1.01963	− .00385	1.08137	− .01632	1.19464	− .04047	1.37828	− .08265
	1.0	1.02000	− .00403	1.08294	− .01710	1.19845	− .04251	1.38584	− .08706
	1.2	1.02072	− .00427	1.08596	− .01815	1.20585	− .04534	1.40068	− .09350
		$\theta = 15^\circ$		30°		45°		60°	
		R	I	R	I	R	I	R	I
$\lvert\Gamma(iq+1)\rvert^2 F(\frac{1}{2}, iq+1, 2; \cos^2 \frac{1}{2}\theta)$	$q =$ .6	.7095	.4385	.7860	.4146	.8058	.3087	.7490	.1536
	.65	.69276	.39466	.72420	.29958	.71174	.21419	.68282	.14880
	.73	.55753	.35519	.60153	.28196	.60321	.20689	.58587	.14696
	.8	.45668	.31610	.50619	.26071	.51679	.19477	.50737	.13951
	.9	.33924	.25888	.38940	.22630	.40853	.17392	.40761	.12644
	1.0	.24990	.20523	.29480	.19062	.31824	.15116	.32318	.11172
	1.2	.13556	.12009	.16282	.12565	.18614	.10692	.19660	.08208

		90°		120°		150°	
		R	I	R	I	R	I
$F(\frac{1}{2}, iq+1, 2; \cos^2 \frac{1}{2}\theta)$	$q =$ .6	1.15909	.11999	1.06981	.04614	1.01722	.01058
	.65	1.15697	.12946	1.06946	.04997	1.01720	.01146
	.73	1.15321	.14560	1.06885	.05603	1.01717	.01287
	.8	1.14969	.15857	1.06826	.06144	1.01714	.01410
	.9	1.14403	.17771	1.06732	.06907	1.01708	.01587
	1.0	1.13773	.19661	1.06628	.07668	1.01703	.01763
	1.2	1.12326	.23360	1.06386	.09185	1.01689	.02115
	1.5	1.09616	.28577	1.05942	.11440	1.01665	.02644
	2.0	1.04129	.36577	1.04992	.15140	1.01611	.03523

TABLE VII (A)

		$\theta = 15°$		30°		45°		60°	
		R	I	R	I	R	I	R	I
	$q =$ .6	− 5.561	−16.390	1.9824	−3.6782	1.4360	− .9976	.8633	− .2541
	.65	− 9.129	−16.378	1.6849	−4.2013	1.4717	−1.1925	.9213	− .3190
G_0	.73	−15.219	−14.554	.9687	−4.9906	1.4697	−1.5380	1.0008	− .4441
	.8	−20.339	−10.905	.0927	−5.5705	1.3967	−1.8666	1.0527	− .5759
	.9	−25.856	− 2.349	−1.5383	−6.0759	1.1548	−2.3548	1.0880	− .7991
	1.0	−27.314	9.279	−3.5156	−6.0115	.7294	−2.8214	1.0631	−1.0581
	1.2	−12.201	32.395	−7.5880	−3.5014	− .6943	−3.4274	.7697	−1.6271
	1.5								
	2.0								
	$q =$ .6	.2313	.0475	.2082	.0414	.1770	.0293	.1454	.0098
	.65	.2287	.0559	.2057	.0505	.1747	.0389	.1435	.0193
G_1^E	.73	.2235	.0653	.2008	.0610	.1702	.0507	.1395	.0316
	.8	.2274	.0694	.2013	.0665	.1669	.0577	.1335	.0395
	.9	.2127	.0696	.1910	.0692	.1616	.0632	.1318	.0471
	1.0	.2062	.0639	.1858	.0665	.1578	.0642	.1287	.0509
	1.2	.1943	.0435	.1774	.0514	.1530	.0559	.1255	.0487
	1.5								
	2.0								
	$q =$ .6	.1542	− .0761	.1607	.0610	.1157	.1271	.0697	.1571
	.65	.1387	− .1011	.1659	.0441	.1235	.1193	.0754	.1543
$G_1^{F_0}$	.73	.1044	− .1360	.1709	.0143	.1360	.1043	.0860	.1483
	.8	.0656	− .1582	.1707	− .0140	.1466	.0886	.0966	.1414
	.9	.0004	− .1711	.1615	− .0564	.1596	.0615	.1130	.1285
	1.0	− .0676	− .1570	.1403	− .0977	.1684	.0295	.1298	.1113
	1.2	− .1635	− .0495	.0612	− .1595	.1648	− .0448	.1589	.0627
	1.5								
	2.0								

TABLE VII (B)

90°		120°		150°		180°	
R	I	R	I	R	I	R	I
.2974	.0387	.0931	.0364	.0188	.0104	0	0
.3227	.0380	.1005	.0402	.0202	.0116		
.3635	.0321	.1127	.0456	.0224	.0135		
.3994	.0215	.1239	.0492	.0244	.0150		
.4499	−.0043	.1406	.0521	.0275	.0169		
.4979	−.0448	.1584	.0517	.0309	.0182		
.5737	−.1756	.1964	.0376	.0387	.0187		
.5668	−.4910	.2486	−.0263	.0525	.0118		
−.0747	−.9972	.2238	−.2470	.0661	−.0278		
.1012	−.0480	.0827	−.1079	.0713	−.1434		
.1006	−.0406	.0844	−.1035	.0754	−.1403		
.0985	−.0309	.0855	−.0979	.0802	−.1363		
.0936	−.0241	.0864	−.0941	.0842	−.1336		
.0919	−.0171	.0824	−.0907	.0841	−.1315		
.0877	−.0125	.0779	−.0891	.0830	−.1311		
.0801	−.0098	.0651	−.0896	.0740	−.1347		
.0636	−.0165	.0416	−.0926	.0438	−.1458		
.0455	−.0305	−.0220	−.0865	−.0455	−.1433		
.0003	.1719	−.0411	.1669	−.0625	.1601		
.0007	.1717	−.0440	.1660	−.0670	.1581		
.0034	.1714	−.0467	.1650	−.0723	.1554		
.0076	.1711	−.0472	.1646	−.0751	.1539		
.0166	.1703	−.0452	.1650	−.0765	.1530		
.0287	.1685	−.0400	.1662	−.0751	.1536		
.0606	.1597	−.0210	.1695	−.0642	.1583		
.1184	.1229	.0269	.1685	−.0287	.1682		
.1695	−.0194	.1308	.1094	.0723	.1545		

TABLE VIII (A)

		$\theta = 15°$		30°		45°		60°	
		R	I	R	I	R	I	R	I
G_1^{Φ}	$q =$ .6	1.4037	−1.6269	.9867	−.1562	.5692	.1272	.3283	.1666
	.65	1.1913	−1.8108	.9943	−.2271	.5884	.1094	.3401	.1659
	.73	.7630	−2.0428	.9880	−.3526	.6185	.0747	.3614	.1640
	.8	.3104	−2.1584	.9577	−.4774	.6414	.0308	.3815	.1541
	.9	−.4114	−2.1232	.8662	−.6659	.6646	−.0502	.4110	.1290
	1.0	−1.1259	−1.8065	.7111	−.8474	.6702	−.1505	.4391	.0904
	1.2	−2.0026	−.3885	.2160	−1.0877	.6021	−.3876	.4772	−.0268
	1.5								
	2.0								
F	$q =$ .6	.4561	−.0883	.3577	.3044	.1135	.4625	−.1242	.5000
	.65	.4291	−.1713	.3906	.2557	.1505	.4452	−.0957	.4991
	.73	.3535	−.2921	.4321	.1671	.2106	.4102	−.0454	.4951
	.8	.2567	−.3763	.4537	.0805	.2614	.3709	.0024	.4880
	.9	.0820	−.4445	.4569	−.0527	.3299	.2998	.0773	.4692
	1.0	−.1114	−.4345	.4204	−.1876	.3854	.2115	.1550	.4378
	1.2	−.4077	−.1730	.2242	−.4072	.4330	−.0069	.3038	.3272
	1.5								
	2.0								
G	$q =$ .6	−3.772	−18.046	3.338	−3.732	2.2980	−.7138	1.4070	.0796
	.65	−7.570	−18.234	3.051	−4.333	2.3584	−.9248	1.4804	.0205
	.73	−14.128	−16.668	2.329	−5.268	2.395	−1.308	1.5879	−.1002
	.8	−19.735	−13.152	1.422	−5.995	2.3518	−1.6895	1.6645	−.2408
	.9	−26.054	−4.574	−.319	−6.729	2.1408	−2.2802	1.7440	−.4944
	1.0	−28.301	7.379	−2.478	−6.890	1.7259	−2.8782	1.7609	−.8054
	1.2	−14.173	32.001	−7.133	−4.697	.2257	−3.8041	1.5315	−1.5424
	1.5								
	2.0								

TABLE VIII (B)

90°		120°		150°		180°	
R	I	R	I	R	I	R	I
.1095	.1097	.0328	.0479	.0064	.0116		
.1114	.1150	.0325	.0506	.0061	.0123		
.1158	.1222	.0323	.0544	.0058	.0132		
.1213	.1266	.0327	.0573	.0057	.0139		
.1313	.1302	.0343	.0607	.0057	.0148		
.1440	.1301	.0371	.0633	.0060	.0156		
.1759	.1165	.0464	.0653	.0075	.0167		
.2261	.0556	.0682	.0577	.0119	.0166		
.2183	− .1447	.1027	.0031	.0221	.0083		
− .4747	.4057	− .6717	.2531	− .7836	.1541	− .8252	.1256
− .4652	.4088	− .6722	.2462	− .7866	.1405	− .8282	.1105
− .4447	.4181	− .6696	.2424	− .7885	.1271	− .8298	.0951
− .4209	.4295	− .6633	.2457	− .7890	.1234	− .8314	.0903
− .3804	.4505	− .6518	.2613	− .7830	.1302	− .8230	.0950
− .3292	.4736	− .6336	.2878	− .7749	.1508	− .8140	.1139
− .1980	.5143	− .5762	.3671	− .7456	.2268	− .7843	.1857
.0369	.5140	− .4043	.5146	− .6494	.4022	− .7433	.3595
.4233	.2126	.0653	.6132	− .2550	.6943	− .3532	.7195
.5086	.2725	.1677	.1435	.0340	.0387		
.5356	.2842	.1735	.1534	.0347	.0417		
.5814	.2950	.1839	.1671	.0362	.0459		
.6220	.2952	.1959	.1771	.0392	.0493		
.6899	.2791	.2122	.1873	.0408	.0534		
.7586	.2413	.2334	.1921	.0448	.0565		
.8904	.0908	.2870	.1829	.0561	.0591		
.9750	− .3290	.3854	.1074	.0796	.0510		
.3586	−1.1919	.4355	− .2209	.1151	− .0083		

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FOSSIL PARASITIC HYMENOPTERA OF THE FAMILY SCELIONIDAE FROM BALTIC AMBER

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The Scelionidae form the largest family of the hymenopterous superfamily Serphoidea. At present approximately 1600 living species are known, distributed among 170 genera. The first entomologist who attempted to deal with the family as a whole for any region was Ashmead who included a consideration of all the North American species known to him in his "Monograph of the North American Proctotrypidae," published in 1893. Regarding the group as a subfamily he recognized four tribes, *viz.*, Telenomini, Baeini, Teleasini and Scelionini. Later he raised these to the rank of subfamilies and this has been generally adopted by later workers. Kieffer has added the Platygastrinae as another subfamily although Ashmead separated these as an independent family, and I think rightly so.

Aside from the Oligocene species described on the following pages, our present knowledge concerning fossil Scelionidae is exceedingly meagre. Altogether only six species have previously been made known. These include three from Canadian amber of Cretaceous age: *Baeomorpha dubitata* Brues, *Baryconus fulleri* Brues and *Proteroscelio antennalis* Brues. The second of these belongs to a living genus, but the two others are not closely related to any recent ones. From the Oligocene of Gurnet Bay Cockerell has described *Macroteleia veterna* which is from his description and figure apparently a member of this living genus or at least of some closely related one. From the Baltic amber only one species was previously known, *Hadronotus electrinus* Cockerell. Finally Statz includes among his middle Oligocene insects from the Siebengebirge, as *Scelionites capitatus* Statz, a small hymenopteron which may belong to this family, perhaps to the subfamily Scelioninae. Two species from Zanzibar copal, *Calotelea aurantia* Westwood and *Ceratobaeus incertus* Meunier can hardly be considered as actually fossil.

In the living fauna the subfamily Scelioninae is by far the largest, including nearly half of the species in the family. This proportion holds true of the Oligocene fauna also as approximately half of the species so far discovered are Scelioninae. Of the other subfamilies, the Teleasinae does not appear in the amber collections at all, which is rather unexpected as about one-fifth of the recent species fall into this group which shows no characters that appear to be of particularly specialized nature. The Telenominae are represented in the amber by only two species, although they form about one-quarter of the recent fauna. This subfamily is distinguished from the others by the lack of lateral carinae on the abdomen, a character that is quite definite in recent genera, but in several of the Oligocene genera this difference is not clear-cut and cannot be relied upon with such assurance. On this account it appears that the Telemoninae were not at that time so sharply differentiated as they now are from the rest of the family. This condition is to be noted also in the case of the subfamily Baeinae. In the living fauna this is the smallest one, containing less than one-tenth of the species. It is distinguished by the form of the antennae which have a reduced number of joints in the female, due to the fusion of the three or four apical joints into a large oval or ovate club-joint. In several living genera this fusion is not entirely complete as there remain faint traces of sutures on one or both sides of this club-joint, although there is a complete anchylosis of the sections. On account of these sutures there has been some difference of opinion as to whether the genera in question should be placed in the Baeinae or removed to the Scelioninae. In the amber there is a disproportionately large number of Baeinae (nearly 20%) and all of the genera are those which show indications of sutures on the club-joint. As this is obviously a generalized condition we may regard the Baeinae of the amber as on the whole more primitive than its recent representatives although some are very highly specialized in other ways, *e. g.*, in the development of aptery, and the occurrence of a highly developed abdominal horn in one species. Undoubtedly Baeinae with completely fused antennal club will be found in the Oligocene as one form from Canadian amber of Cretaceous age is of this type.

It will be seen therefore that the several subfamilies were not as clearly distinguishable in the amber fauna as they are at the present day, and that their proportionate abundance was clearly, although not very fundamentally, different.

Two remarkable genera remain yet to be mentioned. One of these, Uroteleia, is a very aberrant form, at once recognizable by a long thinly chitinized tubular extension of the abdomen. This genus might perhaps be placed in another family (Diapriidae), but on a later page its affinities are given in more detail.

Still more confusing is a very striking insect with 14-jointed antennae that I believe is a scelionid although it must be admitted that its affinities are by no means clear. No other scelionid has more than twelve joints in the antennae, except one genus from the Canadian amber which I described in 1937. Such discoveries are very disconcerting and add to the perplexity of interrelationships that must be dealt with when we compare faunas of different geological ages on the basis of a taxonomy built of necessity on the more extensively known living fauna.

The systematic account that follows is based on the examination of more than 300 specimens, including a series belonging to the Museum of the University of Königsberg, loaned to me for study some years ago, as well as those in the Haren Collection belonging to the Museum of Comparative Zoology at Harvard University. The combined collections contain numerous species in addition to those dealt with here, but these are not sufficiently well preserved for complete examination and it would serve no useful purpose to give them names.

Nearly all of the accompanying illustrations are from drawings made by Mrs. A. S. O'Connor. In spite of the difficulties in dealing with such minute amber insects, she has succeeded in demonstrating the important characters with great clarity. The remainder were drawn by Mrs. Imlah some years ago at the time the first collection was received from the Königsberg Museum.

Dissolcus Ashmead

Bull. U. S. Nat. Mus., No. 45, p. 164 (1893).

There is a single species, represented by two female specimens that agrees very well with the living forms of this genus.

Dissolcus electra sp. nov.

♀. Length 1.5 mm. Shining and apparently entirely black, including the legs and antennae; wings hyaline, with the veins dark brown. Head large, very long antero-posteriorly when seen from above; ocelli in a large triangle, the posterior ones very near to the eye-margin; vertex, front and probably the face also strongly shagreened. Eyes large and coarsely granulated. Antennae 12-jointed, with seven-jointed club, the club fusiform, rather slender and tapering apically from near the base; scape long, reaching well upwards toward the vertex; pedicel much longer than thick, strongly constricted basally, nearly as long as the first flagellar joint which is fully twice as long as thick and not conspicuously narrowed basally; second to fourth flagellar joints short, gradually wider and the fourth forming quite clearly a part of the club; club-joints transverse, the first and the penultimate not so strongly so; apical joint triangular, longer than thick; head behind the eyes smooth, much widened below on the cheeks and with some faint, radiating striae extending over the malar space from the bases of the mandibles, the latter bidentate at tips. Thorax above shining, shagreened on the mesonotum; parapsidal furrows deeply impressed behind, but not extending in front of the middle. Scutellum polished, with a marginal line of small punctures along its posterior margin; metanotum very short its posterior edge straight, margined like the scutellum. Propodeum short, sharply declivous, finely rugose. Mesopleurae smooth, irregularly punctate along the sutures; sides of metathorax and propodeum rugulose. Abdomen visible only from below; first segment very short, its sternite coarsely striate; second longest, about one-third longer than the third, faintly striate at the sides; fourth and following much shorter. Marginal vein very short, less than half as long as the stigmal; postmarginal about as long as the stigmal.

Type in the Collection of the University of Königsberg Museum, without number. A second specimen No. Z3671 may be the same species but the preservation is not good enough to permit a positive statement.

Sembilanocera gen. nov.

(Fig. 1)

There are a number of specimens representing a single species which is quite unique in having 9-jointed, strongly clubbed antennae in the female, in combination with a normally developed wing venation. This number does not occur elsewhere in the Scelionidae so far as I am aware, although it is not unknown in the related family Platygastridae which is often not given separate rank. There, however, the wing venation is completely absent or reduced to a single clubbed discal vein and the general structure is quite different, especially in the form of the thorax and doubly geniculate antennae. In general habitus, except for the jointed antennal club, there is a similarity to members of the subfamily Baeinae. On the other hand the quite obsolete lateral carinae of the abdomen show a relationship to the Telenominae where the genus had perhaps better be placed with the understanding that it would seem to be annectant to the Baeinae.

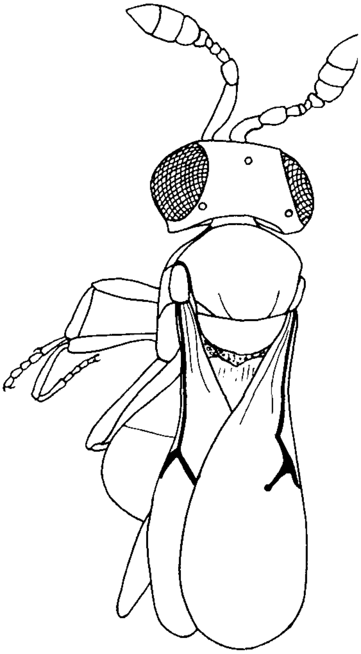

FIGURE 1. *Sembilanocera clavata* Brues, ♀.

♀. Head transverse, the eyes large and the lateral ocelli close to the eye margin. Antennae short, 9-jointed, with large pedicel; basal flagellar joints minute; club very large, composed of three entirely independent joints. Thorax much narrower than the head; parapsidal furrows indicated by posterior impressions next to the scutellum which is simple. Abdomen short and broad; much narrowed at the base; third segment the longest and widest. Wings with the submarginal vein extending to the middle; marginal vein very short; stigmal vein long, knobbed at tip; postmarginal distinct, but somewhat shorter than the stigmal.

Type: *S. clavata* sp. nov.

Sembilanocera clavata sp. nov.

(Fig. 1)

♀. 0.9–1.1 mm. Appearing black with the legs and antennae and perhaps also the abdomen brownish; wings hyaline or somewhat infuscated, the veins brown. Head above faintly roughened; ocelli widely separated in a rather low triangle, the lateral ones practically contiguous with the eye. Eyes large, approaching the occiput above, but more widely separated from the gular margin below; malar space large, with radiating striae that extend upwards from the base of the mandible to the eye (almost exactly as in *Mirotelenomus angulatus* described on another page!). Scape one-third the length of the antenna, not much thickened; pedicel large, oval, narrowed at the base, about half as long as the scape; first three flagellar joints extremely small, the first longer than wide, the second globular, as wide as the first, third wider, transverse; fourth flagellar joint larger and very strongly transverse, but much narrower than the following and hardly to be considered as a part of the club; the three-jointed club fusiform, longer than the pedicel and funicle together, its first joint transverse, second quadrate and third triangularly pointed. Mesonotum faintly shagreened; scutellum weakly punctulate; parapsidal furrows deeply impressed behind, but entirely wanting anteriorly. Abdomen finely striate on the first tergite, this sculpture extending to the middle portion of the second, except at apex; first tergite half the length of the second; third one-half longer than the second; fourth as long as the first; following ones very short. Stigmal vein moderately oblique.

Type: Collection of the University of Königsberg (without number). Paratype, V141. Also four other specimens in the Königsberg Collection and one in the Museum of Comparative Zoology.

Mirotelenomus Dodd

Trans. Roy. Soc. South Australia, vol. 37, p. 173 (1913).

Dodd, *ibid.*, vol. 50, p. 312 (1926).

Mirotelenomus angulatus sp. nov.

(Fig. 2)

♀. Length 1.6 mm. Color apparently wholly black, with the legs a little lighter; wings faintly infuscated, with dark brown venation. Head large, seen from above slightly more than twice as wide as thick; upper surface with strong, well separated punctures; occiput more or less angularly concave, the eyes widely separated from the posterior margin of the head. Ocelli in a low triangle, the anterior one much larger than the lateral ones which are about twice as far from the anterior one as from the eye-margin. Malar space conspicuously striate, the striae spreading out fan-shaped from a point just anterior to the base of the mandible. Antennae 12-jointed; scape thick and rather short; pedicel considerably longer than thick, strongly narrowed basally; first to fourth flagellar joints gradually thicker, the first wider than long, the third quadrate and the fourth transverse; club of six joints, the first scarcely larger than the preceding one, but clearly a part of the club which is five times as long as thick; middle four joints of club transverse, the first of these more strongly so. Mandibles slender, with two teeth at apex. Thorax very broad, as wide as the head; mesonotum wider than long, without trace of parapsidal furrows, the pronotum visible as a narrow band, not widened laterally. Scutellum with a foveate suture and a coarse punctate line along its hind margin; nearly half as long as the mesonotum and fully two and one-half times as wide as long, its surface sculptured like the mesonotum. Postscutellum with a slight median projection. Abdomen short, broadly oval and bluntly rounded at apex; first tergite extremely short; second nearly as long as the third, sharply longitudinally striate on its basal half, apically obsoletely punctulate as is the rest of the dorsal surface of the abdomen. The sides of the thorax are not clearly to be seen, but the pleurae appear to be coarsely sculptured at least in part. Legs short and stout. Submarginal vein sharply bent downward, almost angulate before the apex; marginal vein very short, almost punctiform; stigmal vein long, not strongly oblique, without a distinct knob; postmarginal vein strong, distinctly longer than the stigmal.

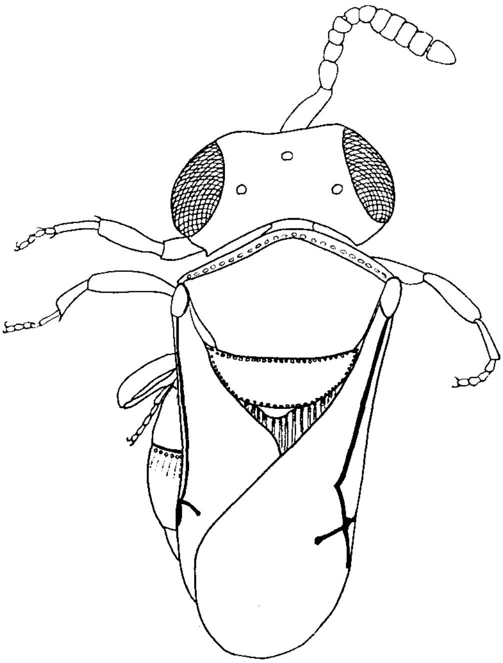

FIGURE 2. *Mirotelenomus angulatus* Brues, ♀.

Type: No. 10,590, Museum of the University of Königsberg.

This is a very striking species, represented by an exceptionally well preserved specimen, but I have had considerable difficulty in placing it satisfactorily in any genus. It will be noted that the marginal vein is extremely short and the lateral margins of the abdomen are not at all carinate while the antennae are 12-jointed. The type has the habitus of certain genera of Scelioninae like Hadronotus, but it resembles certain Telenomus (sens. lat.) also in spite of the 12-jointed antennae and very short marginal vein. Dodd does not indicate directly where his genus Mirotelenomus should be placed although it is put between two genera of Scelioninae in his paper and no reference is made as to the presence of a lateral carinate margin on the abdomen which is clearly lacking in the amber species. So far only living Australian species are included in Mirotelenomus. Kieffer has proposed the genus Hadrophanurus (1926) for Ashmead's North American *Telenomus pennsylvanicus* which resembles the amber species, but he overlooked Dodd's Mirotelenomus and consequently made no comparisons with it.

Parabaeus Kieffer

Bull. Ent. Soc. France, 1910, p. 294.

There is a species in the amber which is probably congeneric with *Parabaeus ruficornis* Kieffer, known from the Seychelles, but the insect is stouter-bodied than the living form and may represent a new genus. However the relationship is certainly close. There is further a close similarity to *Mirobaeus tasmanicus* Dodd from Tasmania, but the latter has one more joint in the antenna and has been placed in another subfamily by Kieffer apparently on this account. From both the living fauna and the forms here described from the amber it is evident that the transitions between a solid and jointed club exist. Following is a résumé of what appear to be generic characters in the amber species.

Very small, completely apterous species. Head large, broadly oval; eyes large; ocelli very widely separated, the posterior ones next to the eye-margin; cheeks large, the malar space very long as the eyes are inserted high up on the sides of the head. Antennae 10-jointed; scape long; pedicel and two following joints longer than wide; third and fourth flagellar joints small, followed by a large pointed club of four joints, these separated from one another by oblique sutures. Thorax, seen from above longer than wide; pronotum separated, but the scutellum apparently not separated. Abdomen broadly oval, wider than and not much longer than the thorax. Legs with very stout, clavate femora and tibiae, but with the tarsi extremely slender.

Parabaeus pusillus sp. nov.

(Fig. 3)

♀. Length 0.8 mm. Reddish brown as preserved, with the head darkened above and this may quite probably have been the color in life. Head rounded above, less than twice as wide as long in dorsal view; front, vertex and occiput very finely, irregularly aciculate; occipital margin broadly and shallowly excavated. Antennae about as long as the body; scape nearly as long as the width of the head, much thickened just beyond the middle, only slightly curved; pedicel slender, much narrowed at the base, fully twice as long as wide; first flagellar joint as long as the pedicel, but not so thick; second flagellar joint thicker, but little longer than wide; two following minute, globose; club large, closely compacted, oval-acuminate with the sutures between its four joints very strongly oblique when seen from the side. Face convex, smooth; malar space very large, without furrows, its surface finely aciculate, with the lines curved and more or less parallel with the eye margin. Pronotum very deeply excavated behind, its sides extending backwards nearly to the middle of the thorax; mesonotum smooth or but faintly sculptured; without trace of parapsidal furrows, and as well as can be seen, not separated from the scutellum by any suture. Abdomen exhibiting no sutures above so far as can be seen, its extreme basal margin raised and provided with several foveae medially; dorsal surface highly convex.

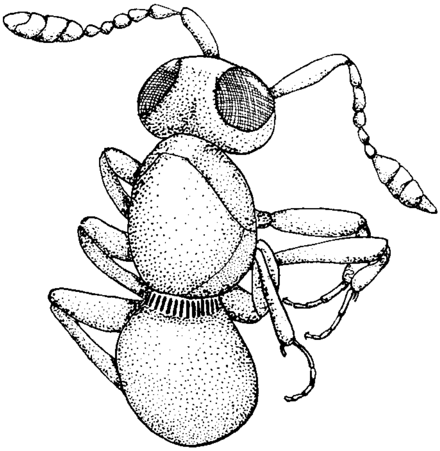

FIGURE 3. *Parabaeus pusillus* Brues, ♀.

Type: University of Königsberg collection, No. 9024.

There is only a single specimen of this very peculiar species. It is very well preserved, but on account of its very small size and the dark color of the piece of amber, some details of bodily structure are hard to see clearly.

Aneurobaeus Kieffer

André, Spéc. Hymén. Europe et Algérie, vol. 11, p. 87 (1912).

Aneurobaeus collaris sp. nov.

(Fig. 4)

♀. Length 1.0 mm. Stout-bodied, with the head and abdomen turned downward so that the dorsal outline of the body is strongly convex. Color apparently entirely black. Head wider than the thorax. Eyes rather small, set well forward and high up so that the cheeks are long and wide; ocelli in a large triangle, the posterior ones quite near to the eye and not far from the carinate occipital margin. Surface of front and occiput microscopically roughened or reticulate. Antennae 7-jointed, stout; scape very much thickened beyond the middle where it is as broad as the club-joint; pedicel one-third longer than thick; first

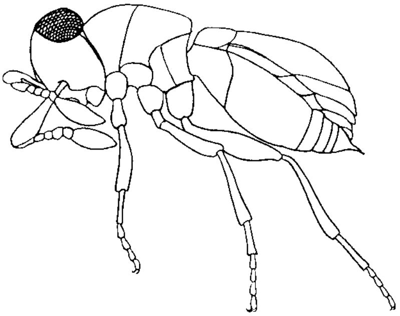

FIGURE 4. *Aneurobaeus collaris* Brues, ♀.

flagellar joint shorter and narrower; second to fourth subequal, as wide as the first, more or less quadrate; club-joint entirely solid, without trace of sutures, elongate-ovate. Prothorax narrowed medially, but clearly visible from above, its posterior margin curving obliquely backwards on the sides, the posterior angles extending beyond the middle of the thorax. Pronotum sculptured like the head. Mesonotum long, narrow, without trace of furrows, its surface shining, slightly shagreened; scutellum not separated; propodeum very short. Abdomen as long as the thorax; first segment short, much wider than long and only about half the width of the second; its upper surface irregularly reticulate. Second tergite occupying most of the abdomen, very convex and wider than the thorax; basal half microscopically reticulate, distinctly longitudinally aciculate on the basal half, the aciculations growing more noticeable basally and medially; third tergite forming a narrow band, fourth scarcely visible. Venter with all six sternites present, the second occupying less than one-half of the venter; the first coarsely longitudinally striate. Legs stout, all the femora and tibiae very strongly clavate.

Type: Museum of Comparative Zoology, No. 8095.

This species is superficially very similar to *Parabaeus pusillus* Brues described on another page. However, the antennal club is solid, without sutures and the antennae are longer and more slender; furthermore it is considerably larger and has the habitus of Aneurobaeus although the pronotum is longer than in that genus and clearly exposed in dorsal view. It differs at once from Baeus in the long second (not third) tergite. The recent species of the genus occurs in Ceylon.

Pseudobaeus Perkins

Fauna Hawaiiensis, vol. 2, p. 620 (1910).

There are more than fifty female specimens of minute winged Baeinae and a smaller number of males that I have referred to this genus although they differ in having the parapsidal furrows present near the posterior edge of the mesonotum. The costal margin of the wing bears a series of long cilia which extend as far as the tip of the postmarginal vein but disappear toward the base of the wing. The several described species occur in Hawaii and Australia and are known only in the female sex.

Pseudobaeus fecundulus sp. nov.

(Fig. 5)

♀. Length 0.8–1.1 mm. Apparently black, with the wings hyaline; venation dark brown. Head considerably wider than the thorax; about twice as wide as long when seen from above; occiput gently concave, with a fine marginal line. Ocelli in a large triangle, the posterior ones practically contiguous with the eye-margin. Face smooth and shining; front and vertex very finely roughened or shagreened, cheeks and temples smooth, polished, with a few minute, scattered punctures. Malar space as long as the antennal scape, with a series of clearly defined striae extending from the lower corner of the eye and converging to the base of the mandible. Antennae seven-jointed; scape two-thirds as long as the remaining joints together; pedicel fully as thick as the scape, nearly twice as long as thick; four following joints subequal, very small, moniliform; club-joint a little more than twice as long as thick, without sutures or with just the faintest trace of such in certain lights on the upper side of the joint. Mesonotum and scutellum shagreened, separated by a straight, simple suture; parapsidal furrows indicated as short, widely separated impressions on the posterior third of the mesonotum. Scutellum twice as wide as long, the posterior edge raised and separated by a submarginal, weakly punctate line. First segment of abdomen transverse, fully twice as wide as long, evenly longitudinally fluted or coarsely striate; much narrower than the propodeum; second tergite much widened behind, coarsely longitudinally striate at the base, the striae extending back medially as very fine lines nearly to the apex of the segment; third tergite wider than, and one-half longer than the second, as wide as the thorax. Marginal vein short, slightly thickened; stigmal vein long, oblique, faintly curved, knobbed at tip; postmarginal vein very distinct, longer than the stigmal.

Type: No. 6728, in the Museum of the University of Königsberg.

Besides the type there are in the Königsberg collection nine females and in the Museum of Comparative Zoology four that are unquestionably the same species. In addition there are 49 others that are most likely conspecific; at least none of them can be excluded on the basis of characters visible in the individual specimens. Of these latter seven are in the Museum of Comparative Zoology.

The material before me includes also 30 males, six of which are, I believe, certainly this species, while the other 23 cannot be excluded and probably be-

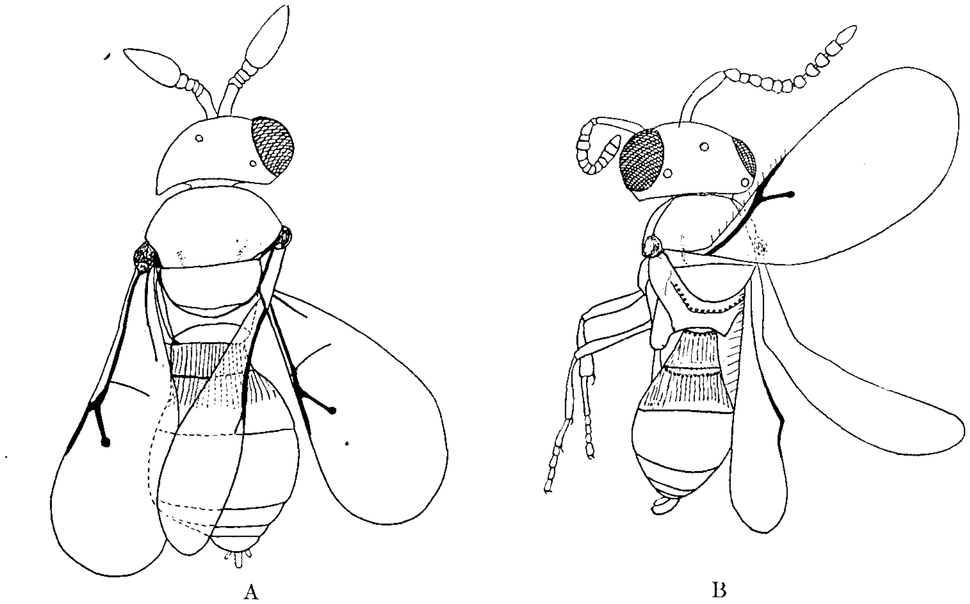

FIGURE 5. *Pseudobaeus fecundulus* Brues. A, ♂; B, ♀.

long here. Considering the great abundance of the species in the amber there can be little question that the males are properly associated, although this would be impossible on morphological grounds alone as this sex is known in only one of the described living species.

♂. Length 0.7–1.0 mm. Similar to the female, but the head and thorax less distinctly sculptured and more shining. Abdomen more constricted at the base, the petiole somewhat less than twice as wide as long, its striations much finer; the striae of the second tergite are fine also, not stronger at the base of the tergite. Antennae 12-jointed; scape slightly arcuate; following joints of about equal thickness except that the first flagellar joint is narrowest and the following joints grow imperceptibly wider to the penultimate one which is wider than the pedicel; the flagellar joints, except the last, are more or less moniliform. Legs much more slender than in the female.

Allotype: No. 8143, Museum of Comparative Zoology.

Ceratobaeoides Dodd

Mem. Queensland Mus., vol. 2, p. 337 (1913).

Ceratobaeoides acuminatus sp. nov.

(Fig. 6)

♀. Length 1.1 mm. Head and thorax black; antennae brownish testaceous; legs, including coxae, brown; abdomen brown below; piceous above, with the base of the basal horn honey-yellow; and with the middle portion of the second and third segments testaceous, this pale area narrowed basally on the third tergite; sixth segment ferruginous. Wings clear hyaline, with very dark venation. Head contracted and noticeably extended downward, the eyes elongate oval, removed from the mandibles by nearly half the head-height. Front and face apparently smooth, the lateral ocelli adjacent to the eye-margin. Antennae 10-jointed; scape half as long as the height of the head, thickest near the base; pedicel large, as thick as and nearly half as long as the scape; first flagellar joint very slender, two-thirds as long as the scape; following three joints minute, moniliform; club large, elongate ovate, composed of four anchylosed joints separated by distinct indications of sutures. Mesonotum smooth; convex, especially in front, without parapsidal furrows; scutellum short, one-fourth as long as the mesonotum, its basal groove foveate and its hind edge raised with a marginal line of foveae. Thorax almost truncate, the very steep slope of the propodeum nearly straight and in line with the posterior margin of the scutellum. Abdomen elongate-oval, sharply acuminate at tip; first segment with a dorsal horn at the base that extends to the scutellum. The horn is flattened, wider than usual in related forms with the end broadly rounded; its upper surface is striate, the striae extending over the tip as very fine lines. Second

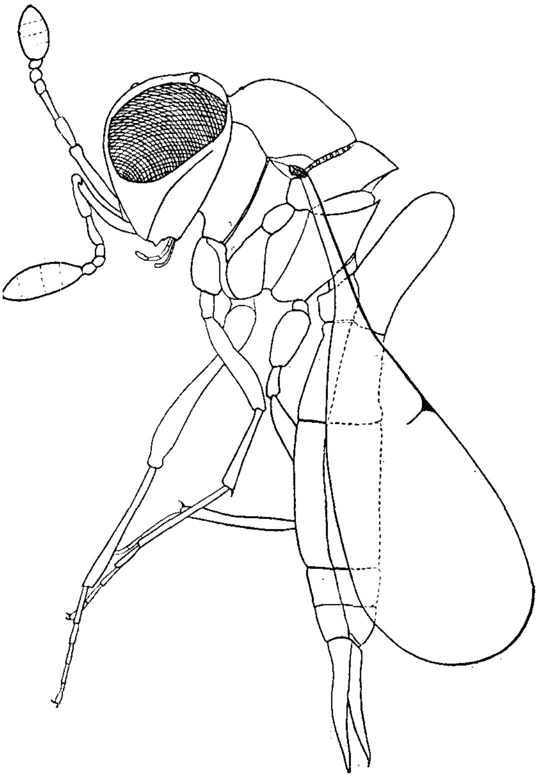

FIGURE 6. *Ceratobaeoides acuminatus* Brues, ♀.

tergite with coarse striae at base, more abbreviated laterally; much wider than long; third twice as long and much wider, about equal in length and breadth; fourth, fifth and sixth very short; seventh projecting as a narrow pointed process and below the seventh sternite projects even slightly further. Wings not reaching the tip of the abdomen, the hind pair not enlarged; marginal vein short, more or less punctiform; postmarginal distinct, but extremely short; stigmal vein very thin, oblique, without knob at apex.

Type: No. 8144, Museum of Comparative Zoology and paratype No. 8145, Museum of Comparative Zoology.

Both specimens are beautifully preserved and the type is as perfect as though carefully dehydrated and freshly mounted in Canada balsam.

The generic reference may not be correct as there are several points in which the fossil species disagrees with Dodd's original description of the genus and the first three Australian species. The abdominal horn is much longer in the amber species and the abdomen is much more acuminate at the tip, while the segmentation of the antennal club is apparently less pronounced. However it runs to this genus in Dodd's key (Trans. R. Soc. South Australia, vol. 38, p. 58; 1914) and also in Kieffer's key to the genera of Scelioninae to which subfamily this author transfers it in Das Tierreich (Lief. 48, p. 264; 1926) although he retains several other genera with obsoletely jointed club in the Baeinae. From the latter the fossil species differs much more widely. A species later added by Dodd *(Ceratobaeoides turneri)* is much more similar to the fossil species in the form of the abdomen and length of its basal horn.

Brachyscelio gen. nov.

(Figs. 7, 8)

Body short and very stout, the head large and broader than the thorax; abdomen short, extending beyond the wings which appear to be slightly reduced in size. Ocelli close together, placed far forward on the vertex. Antennae (♀) 12-jointed, strongly geniculate; scape stout, excavated at tip to receive the pedicel; flagellum stout throughout, all the joints together forming a long, fusiform, pointed club, widest at its middle. Eyes large, widely separated; occipital margin very deeply concave medially. Pronotum very short, forming a narrow arcuate band. Mesonotum twice as wide as long, with complete, curved parapsidal furrows that are close together behind and very widely separated in front. Scutellum short, its basal suture curved backwards on the sides; posterior margin straight, transverse. Postscutellum and propodeum short. Abdomen broadly oval, strongly longitudinally fluted or striate at the base, at least below. Legs rather slender, the femora and tibiae strongly clavate. Wings with a peculiar venation, the submarginal, submedian, basal, marginal and stigmal veins strongly developed, the marginal vein punctiform and separated from the costal margin of the wing (actually the apical part of the submarginal vein is straight and where it ends and the marginal begins cannot be stated).

Type: *B. cephalotes* sp. nov.

This is a very unusual insect and I have been greatly puzzled in attempting to place it satisfactorily in the system. The form of the head and antennae, coupled with the coarse striations at the base of the abdomen, seem to indicate that it belongs to the Scelionidae. However, the wing venation is not compatible with any living member of the family of which I have any knowledge and, moreover, the mesonotum and scutellum are anomalous, recalling certain Bethylidae, although the propodeum is not of the form characteristic of that family and the antennae are strictly of the

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geniculate type with long, strongly differentiated scape. There is no indication of a stigma in the wing, but the marginal vein is quite distinctly separated from the costal edge of the wing. On account of the closed basal cell it appears to be a rather primitive form and similar in this respect at least to Prolapitha Kieffer, Platyteleia Dodd or related genera. The second species is quite different and probably not really congeneric.

Brachyscelio cephalotes sp. nov.

(Fig. 7)

♀. Length 1.3 mm. Apparently entirely black, including the legs and antennae; wings perhaps slightly infuscated, the venation dark and very distinct. Head not more than one-half wider than long in dorsal view; upper surface finely rugulose, with an irregular row of punctures next to the raised occipital margin; face rugulose, with a smooth area above the base of the antennae; malar space with a deep groove. Ocelli in a triangle, the posterior pair about twice as far from one another as from the eye margin. Antennal scape reaching to the anterior ocellus; pedicel longer than wide, as long as the first flagellar joint which is wider at tip but much narrowed basally; second and following flagellar joints of about equal length, each two-thirds as long as the first; these grow wider to the sixth which is almost twice as wide as long, thence the club tapers off to the pointed apical joint so that the entire flagellum forms a long fusiform club. Mesonotum and scutellum faintly shagreened, the parapsidal furrows crenulate as is also the basal suture of the scutellum which bears at each side a much larger circular impression; posterior margin of scutellum with a crenate line. Metanotum and propodeum finely rugose. Second segment of abdomen apparently much longer than the others, strongly striate at base below; apical tergites very short and broad, but the basal ones are not visible in the type. Wings not quite attaining the tip of the abdomen; basal vein nearly perpendicular to the costal margin, shorter than the marginal vein which is nearly twice as long as the stigmal; radial vein slightly indicated in the region of the stigmal; postmarginal absent.

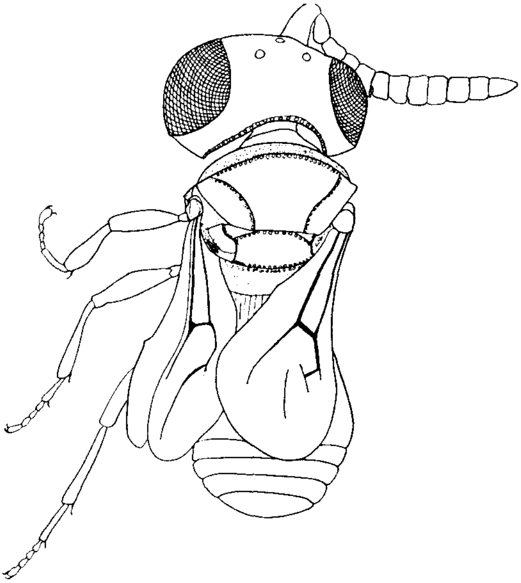

FIGURE 7. *Brachyscelio cephalotes* Brues, ♀.

Type: Museum of Comparative Zoology, No. 8146. No other specimens.

Brachyscelio dubius sp. nov.

(Fig. 8)

♀. Length 2.0 mm. Apparently black, with the abdomen brownish as are also the legs and antennae; wings hyaline with very heavy, dark veins. Head above with some transversely striate sculpture, especially at the sides of the occiput; occipital emargination margined by a series of very large punctures. Ocelli in a small triangle, the posterior pair less than twice as far from one another as from the eye margin. Sides of face delicately aciculate, the striae more or less circular with the base of the antennae as a center. Antennae 12-jointed; scape long and stout; pedicel and first flagellar joint subequal, each narrowed at the base; second flagellar joint very much shorter and thicker, about quadrate or slightly transverse; third and fourth becoming wider; fifth and sixth the largest, not very strongly transverse; following of about equal length and growing slightly narrower with the last acutely triangular. The club is thus composed of seven or eight joints forming an elongate, fusiform thickening. Mesonotum and scutellum smooth; parapsidal furrows curving outwards in front where they are twice as far apart as at the base of the scutellum; basal suture of scutellum a straight, simple, impressed line which ends laterally in a large reticulated impression; posterior edge of scutellum crenate, the scutellum half as long as the mesonotum which is less than twice as wide as long. Metanotum coarsely foveate-reticulate; propodeum reticulate, with a median well defined tooth at the base. Abdomen very broadly ovate; second sternite as long as the three following, striate at the base; third, fourth and

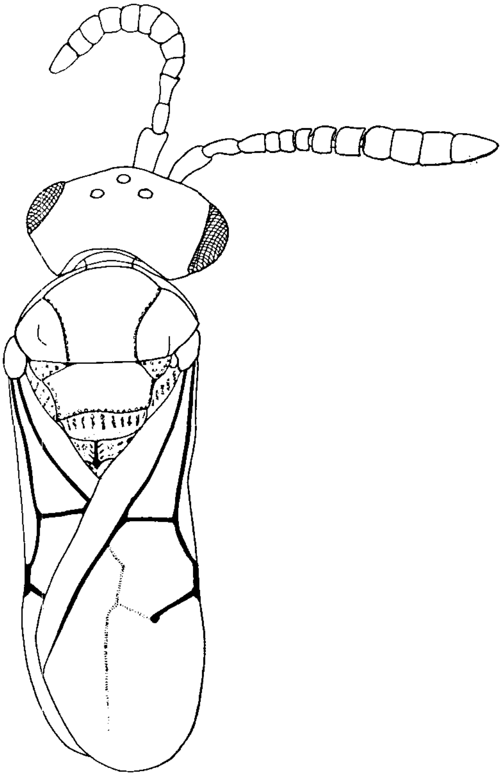

FIGURE 8. *Brachyscelio dubius* Brues, ♀.

fifth sternites decreasing gradually in length; sixth suddenly narrowed, as long as the fourth. Tergites obscured by the folded wings. Tibiae and femora clavate, the latter considerably thickened. Wings with a long submarginal vein attaining the costa beyond the middle of the wing; marginal vein linear, contiguous with the margin of the wing; stigmal vein twice as long as the marginal, straight, not knobbed; basal vein very strong as is also the median vein which extends almost to the wing margin.

Type: Museum of Comparative Zoology, No. 8147. No other specimens.

This insect is similar to the preceding species in general habitus and wing venation, except that the basal cell is not only complete, but the median vein extends far beyond the cell. I feel sure that the two are related but they probably should be separated generically. This I hesitate to do as they cannot be placed in the family with complete assurance.

Sparaison Latreille

Hist. Nat. Crust. et Ins., vol. 3, p. 316 (1802).

There are two species in the amber which I have referred to this genus. One shows a very distinct frontal ridge or carina and the other lacks entirely any elevation on the front. The development of this structure varies in living members of the genus from a very prominent ridge to a very indistinct elevation. Kieffer has proposed Prosparaison for a Malayan form with normal head and on this basis one amber species might be placed there. Sparaison includes species with and without parapsidal furrows and in the single Prosparaison these are absent. In both amber forms they are complete, a condition which exists in all known Nearctic and Austromalayan species of Sparaison.

Sparaison simplicifrons sp. nov.

(Fig. 9)

♀. Length 3.2 mm. Apparently black, with the legs paler apically and the wings brownish, especially on the apical half. Head very thick antero-posteriorly, nearly three-quarters as thick as wide between the eyes (20 : 28), without a distinct lamina or projecting shelf, but the surface is raised as a broad tubercle between the face and vertex; face and upper side of head coarsely rugose-punctate; occipital margin carinate. Antennae with the scape short, not extending much more than halfway to the frontal tubercle; pedicel two-thirds as long as the first flagellar joint; second flagellar joint slightly shorter than the pedicel, widened apically; third shorter, but distinctly wider than long; four following quadrate, forming the thickest part of the club, the last three becoming

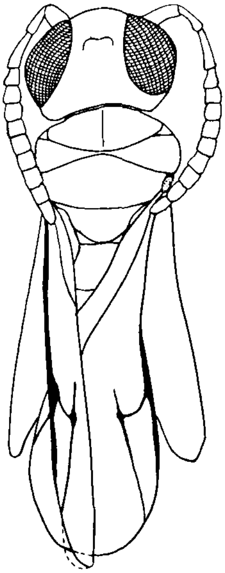

FIGURE 9. *Sparaison simplicifrons* Brues, ♀.

narrower, but of the same length, the last rather acutely narrowed to its tip. Pronotum very short medially, practically lacking a dorsal surface at this point although very long laterally. Mesonotum smooth and apparently not punctate, at least so far as can be seen in quite clear dorsal view; parapsidal furrows distinct, more approximate than usual and strongly convergent behind. Scutellum rugose punctate like the upper surface of the head. Pleurae smooth, at least the propleura and the impression of the mesopleura; sides of propodeum coarsely reticulate, the posterior edge produced as a tooth just above the hind coxa and again above this, the upper tooth separated from the lower one by a semicircular emargination and extending backwards laterally to the extreme base of the abdominal petiole; petiole sharply produced below at base and also distinctly elevated at the base above. First and second tergites coarsely and deeply longitudinally striate; third striate at base; fourth and fifth with the striae punctiform, forming a basal frenum; sixth very short, without basal frenum. Second to fifth sternites each with a basal line of deep impressions separated by a very short striae; first sternite with a punctate basal line. Wings with a distinct, but very narrow pterostigma which gradually narrows apically to continue as a strong postmarginal vein to the tip of the radial cell, stigmal vein long, curved, more widely divergent from the postmarginal vein than in recent members of the genus, and forming an angle of nearly 90° with the radial vein which is well developed for its entire length, extending straight to the wing margin which it attains well before the wing tip.

Type: No. B14548, in the collection of the University of Königsberg Museum. No other specimens.

This species appears to be closely related to Sparaison, but differs in some respects, especially in wing venation as the form of the radial cell is of a much less highly specialized type. However the elevated tubercle on the head, form of thorax and abdomen are very similar to members of this genus from the Malayan region and in possessing parapsidal furrows the fossil form resembles the known Malayan species.

Sparaison amabilis sp. nov.

(Fig. 10)

♀. Length 3.0 mm. Apparently black, polished, the legs more or less brownish and also the base of the antennae; wings hyaline, with brown venation. Face strongly convex, but without any distinct elevated ridge or tubercle; face, front and occiput very deeply and distinctly, sparsely punctate; space behind the eyes nearly smooth, with a coarsely punctate marginal line or frenum that extends upwards along the edge of the occiput which is very deeply emarginate medially. Eyes large, nearly circular in outline, apparently bare; ocelli in a wide triangle, the posterior ones close to the eye-margin. Antennae 12-jointed, with a distinct club; in the type and only female the club shows six large segments, but the base of the flagellum can be seen only in very oblique view and it appears probable that two or three more joints actually form a part of the club which is widest at the eighth and ninth flagellar joints. Pronotum angularly shortened medially; its anterior margin carinate, with a series of large deep punctures; the surface sparsely punctulate. Mesonotum impunctate; with deep, but not broad, foveate parapsidal furrows. Scutellum smooth medially, finely reticulate at the sides; its posterior edge carinate, with a submarginal foveate line. Pleurae coarsely reticulate, the mesopleural furrow deep, smooth. Abdomen only partly visible in the type, its segments about equal in length. Wings with the stigmal thickening well developed; stigmal vein curved.

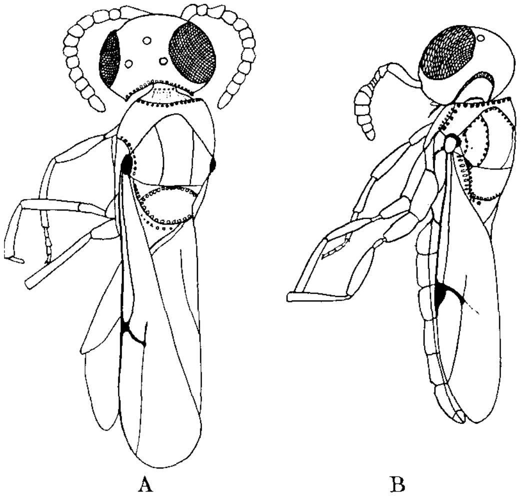

FIGURE 10. *Sparaison amabilis* Brues. A, ♀; B, ♂.

♂. Length 3.1 mm. Essentially similar to the female and included in the same block of amber. Antennae short, most of the flagellar joints stout and more or less quadrate; pedicel small, globose, about one-fourth as long as the curved scape; first flagellar joint about twice as long as the pedicel, strongly widened apically; second flagellar joint about quadrate, slightly shorter than the first and somewhat wider; following gradually narrower and shorter, as wide as long. First segment of abdomen striated, at least at the sides; following segments obscured.

Type: female, No. 8148, Museum of Comparative Zoology. The male is imbedded in the same small block of amber and this fact, in connection with its close anatomical similarity, indicates that the two are conspecific.

Electroteleia gen. nov.

(Fig. 11)

There is a long series of a large, striking species that does not fit in any described genus although in habitus, wing venation and abdominal structure it seems quite surely to be related to Sparaison.

♀. Head rounded or oval, not at all thickened antero-posteriorly. Body not coarsely sculptured, except the propodeum and striate base of abdomen. Antennae long; 12-jointed, with a slender 7- or 8-jointed club. Eyes bare. Parapsidal furrows complete; scutellum and postscutellum simple, not spined or toothed; propodeum deeply excavated at apex to receive the abdominal petiole. Abdominal segments two to five each with a line of deep impressions or very short striae forming a transverse row at the extreme base of both the tergites and sternites. Wings with the basal and radial cell clearly enclosed by vein-like thickenings; marginal vein broadened to form a distinct pterostigma that tapers apically and extends to the tip of the radial cell as the postmarginal vein; stigmal vein long, curved. Legs clavate, not thickened.

♂. Differs from the female by the filiform antennae of rather stout form, the flagellar joints toward the apex each not much more than twice as long as wide. Otherwise the sexes are essentially similar.

Type: *E. stigmatica,* sp. nov.

Electroteleia stigmatica sp. nov.

(Fig. 11)

♀. Length 3.8 mm. Apparently all black, although in some specimens the legs and antennae, except club are paler and this was probably their color in life. Body highly polished. Head smooth above, practically impunctate except for a line of punctures on the cheeks, temples and occiput that follows the anterior edge of a raised marginal line; cheeks faintly and face closely, punctate. Scape of antennae reaching halfway to the vertex, strongly curved basally and swollen apically; pedicel elongate, nearly half as long as the scape; first flagellar joint much lengthened, nearly as long as the scape, slender, especially toward the base; second flagellar joint not much more than half the length of the first, stouter, twice as long as thick; third shorter and wider, fourth wider, slightly longer than thick, following, except the last, subequal, quadrate. Lateral ocelli close to, but not touching the eye-margin. Mesonotum sparsely and very minutely punctate, scutellum nearly smooth. Pronotum very short, its anterior surface separated from the dorsum by a delicate carina. Parapsidal furrows complete, foveolate as is also an anterior and lateral line along the edge of the mesonotum. Base of scutellum with a series of large foveae, apex margined by a row of smaller ones. Propleurae and sides of propodeum coarsely reticulate; mesopleurae punctate below, smooth and longitudinally impressed above, and margined behind by a series of large foveate impressions. Abdomen punctate above, coarsely longitudinally striate on the first tergite except at the extreme sides; second tergite with similar striae that do not extend so far laterally; third tergite with the striae occupying only a semicircular area on its basal half; fourth and fifth with only very abbreviated striae across the base. Venter coarsely punctate except for the very short basal striae that separate the lines of foveate impressions. Stigmal vein strongly, evenly curved, not knobbed at tip; radial vein straight.

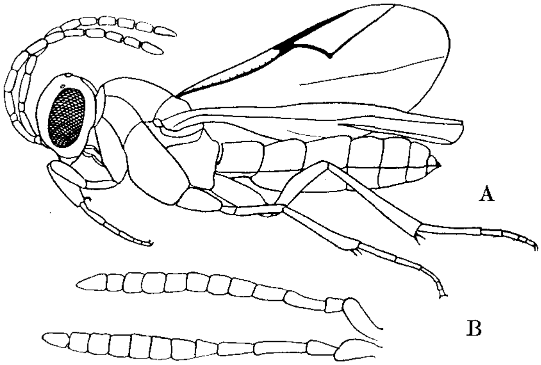

FIGURE 11. *Electroteleia stigmatica* Brues. A, ♂; B, antennae of female.

♂. Differing mainly in the form of the antennae. Pedicel but little longer than thick, scarcely one-third the length of the scape; first flagellar joint nearly as long as the scape, three times as long as thick; following successively a very little shorter and becoming slightly thinner beyond the middle of the flagellum. Abdomen with a frenum at the base of segments two to six.

Type: female, No. 8149, Museum of Comparative Zoology, also nine other females (Museum of Comparative Zoology, Nos. 8151–8154) (Königsberg Museum, Nos. 13889, 2226, B18840 and two without numbers).

Allotype: ♂, No. 8150, Museum of Comparative Zoology. Also nine other males (Museum of Comparative Zoology, Nos. 8155–8159) (Königsberg Museum, No. 9018 and five without numbers).

Hoploteleia Ashmead

Bull. U. S. Nat. Mus., No. 45, p. 227 (1893).

A single species represented by a series of specimens is contained in the present collection. Positive generic reference is difficult, but among the genera so far described in the living fauna the amber species seems to agree most closely with Hoploteleia. Also it is the only fossil form with the thorax conspicuously pilose and this character appears in this genus and also in Rhacoteleia. Dodd believes (Trans. Entom. Soc. London, 1920, p. 338) from an examination of the type and only species of the latter that it is not distinguishable from Hoploteleia which is a large and widespread genus in the recent fauna. Unfortunately in his compilation of the Scelionidae in Das Tierreich (1926) Kieffer has entirely overlooked this paper by Dodd and his treatment of several genera is badly confused on account of this omission. The hairy body is of course not to be regarded as a generic character as it occurs for example elsewhere, in Sparaison, certain subapterous Australian Baryconus, Lapitha, etc.

Hoploteleia doddii sp. nov.

♀. Length 4.4 mm. Entirely black as preserved, with the wings strongly infuscated; the venation strong, very dark brown. Head above rough, the surface irregularly and shallowly reticulated; lateral ocelli very close to the eye, the median one much below the level of the other ones. Head behind the eyes at least to some extent striated, especially on the cheeks. Scape of antennae long, fully equal to the height of the eye, slender; pedicel nearly as thick as the apical part of the scape, one-half longer than thick, not noticeably constricted at the base; first flagellar joint nearly twice as long as the pedicel and nearly as thick; second flagellar joint two-thirds as long as the first; third and fourth successively shorter, the latter no longer than wide and expanded apically so that it appears to form a part of the apical club which includes the following joints (six); this club is not greatly thickened, with its joints about quadrate except the apical one. Surface of mesonotum irregularly wrinkled, with large scattered puncture-like depressions, especially laterally, each bearing a conspicuous hair so that the mesonotum appears strongly hairy in lateral view; parapsidal furrows complete, strongly convergent behind, but there is no indication of a median furrow between them. Groove at base of scutellum deep, but neither broad nor foveate; posterior margin weakly curved, carinate, with a submarginal foveate line. Postscutellum and propodeum deeply reticulate, the former with a median tubercle which is not, however, a true spine or thorn. Pro- and mesopleurae in great part smooth and polished, except for some reticulation next to the propodeum; the latter coarsely reticulate-rugose, except for an elongate polished area near the middle of each side. Abdomen longer than the head and thorax; first tergite short, rather finely longitudinally striate above, the striae extending on to the second tergite, but growing less distinct beyond the middle; third and following tergites closely punctulate; second and third subequal, each nearly twice as long as the first. Legs slender, strongly clavate. Marginal vein very short, slightly thickened; stigmal vein long, straight, strongly knobbed at tip; postmarginal vein extending almost to the wing-tip, unusually thick at base and almost to its apex. Basal and radial veins very feebly indicated by brownish streaks.

Type: No. 8160, Museum of Comparative Zoology.

A second specimen in the Collection of the University of Königsberg is not so well preserved, but undoubtedly the same species, although the antennae are shrunken in preservation and appear at first glance to be much more slender. Also two others (one Museum of Comparative Zoology, No. 8161, and the other Königsberg) may be quite probably placed here.

Hadronotoides Dodd

Arch. Naturgesch., vol. 79A, p. 171 (1913).

There is a single female, of very striking aspect, but not very perfectly preserved which may be a member of this genus. The body is very roughly sculptured, with the habitus of Hadronotus but the apex of the scutellum bears two rather approximate teeth separated by an emargination. If not a true Hadronotoides, it is certainly a close relative. The described recent species are from Australia. In the form of the scutellum it resembles Duarina Dodd, but so far as other characters are visible, does not apear to be similar in other respects.

Hadronotoides dubitatus sp. nov.

♀. Length 3.4 mm. Apparently black, with hyaline wings. Body stout, the head and thorax wider than the abdomen which is small, not extending to the tips of the wings. Head large, the eyes bare; its surface above coarsely, but not very deeply reticulate. Occipital margin deeply concave, margined and with a series of large punctate impressions just inside the margin; vertex flat, the ocelli placed next to the eyes at its front edge, below which the front drops down at a sharp angle; sides of head behind the eyes smooth or faintly punctate, but with an orbital and posterior marginal line of very large punctate impressions which are very conspicuous in comparison with the smooth band between them that leads to the base of the long mandibles which end in two long, acutely pointed teeth. Antennae short and very stout, 12-jointed; scape as long as the eye, thickened apically, about half as long as the remaining joints together; pedicel narrow, longer than wide and longer than the first flagellar joint which is as long as wide, but much narrowed at the base; second joint shorter and thicker, very strongly expanded apically; third very large, transverse; following all transverse; club 8-jointed or perhaps even 9-jointed as the second flagellar joint fits closely into the third. Thorax large, both vertically and horizontally, with unusually coarse, deep sculpture. Pronotum, mesonotum and scutellum deeply and coarsely reticulate. Pronotum with the anterior margin straight and the anterior face vertically truncate; its posterior margin Λ-shaped, almost attaining the front margin medially, but the sides are as long as half the anterior width. Mesonotum without parapsidal furrows. Scutellum about half the length of the mesonotum and separated from it by a not very conspicuous basal groove; sides irregular due to the coarse sculpture, but without distinct teeth, the apex bears, however, a pair of short distinct approximate teeth separated by an arcuate emargination. Pleurae coarsely, irregularly rugose with a few deep striae on the mesopleura above its smooth central impression. Propodeum reticulate, gently declivous behind. Abdomen concealed by the wings from above. From the side, the first tergite is seen to be strongly longitudinally striate, some striae extending onto the second tergite and perhaps weakly on the following one; laterally there are some punctures on all except the first tergite and toward the apex of the abdomen the punctures appear to cover the whole surface; tergites slightly and evenly growing shorter from the base to the tip of the abdomen. Venter convex, with indications of longitudinal striations. Wing venation not clearly visible.

Type in the Museum of the University of Königsberg.

In spite of its imperfect state of preservation this is such a conspicuous form that it seems advisable to describe it at this time.

Hadronotus electrinus Cockerell

Schr. Physikol-Oekonom. Gesellsch., Jahrg. 50, p. 2 (1910).

This species was described from Baltic amber, but there appear to be no specimens in the collections before me.

Ceratoteleia Kieffer

Ann. Soc. Sci., Bruxelles, vol. 32, p. 121 (1908).

In the collections before me there are a large number of specimens of both sexes representing this genus. It appears on the basis of the females that three species are represented in the amber, two of them very closely related. Nearly all belong to one species (*C. proleptica* sp. nov.) which is thus one of the most common members of the family in amber. There are also a great many specimens of males, but I am unable to correlate these with the females, although the proper generic reference is pretty well assured by the strongly striate cheeks which are characteristic of all females found in the amber fauna. Consequently I am obliged to omit any further discussion of this sex. Ceratoteleia occurs in the living fauna in both the Old and New World, so that its occurrence in Baltic amber is not unexpected.

The following key will serve to distinguish the three species.

KEY TO THE BALTIC AMBER SPECIES OF CERATOTELEIA (FEMALES)

1. Postscutellum with a single series of large rectangular foveate impressions, extending entirely across its upper face which slopes downwards posteriorly and lies well below the level of the hind margin of the scutellum; coarse striae of abdominal petiole extending to the extreme base of its protuberance .... *C. caudata* sp. nov.

   Postscutellum not thus sculptured; its central portion elevated and not below the level of the posterior margin of the scutellum; striae of abdominal petiole not extending to its extreme base .... 2.

2. Middle portion of postscutellum broadly rounded behind, fully one-half as long as the scutellum; striae of abdominal petiole replaced by rugose reticulate sculpture only at the extreme base of the segment . . . . *C. succinophila* sp. nov.
Middle portion of postscutellum more or less truncate behind and shorter, much less than half the length of the scutellum; striae on abdominal petiole not extending forward of the middle of the segment . . . . *C. proleptica* sp. nov.

Ceratoteleia caudata sp. nov.

(Fig. 12)

♀. Length 3.5 mm.; tube of ovipositor 1.6 mm. Apparently entirely black, with hyaline wings and dark veins, except the stigmal vein which is paler than usual. Head very thick, more or less globular, seen from above twice as wide as thick; front narrowed above, narrower than the width of the eye at the level of the anterior ocellus; surface of front at the sides coarsely, longitudinally rugose, leaving a smooth median strip below the ocellus. Vertex obliquely striate, the striae passing to the sides and downward behind the eyes, becoming coarser and more conspicuous as they converge and meet the ones along the facial margin of the eyes at a point between the mandible and base of the antenna. Eyes large, strongly convex, bare; ocelli in a rather low triangle, the lateral ones very close to the eye-margin. Antennae 12-jointed, long, with a slender, not very abrupt club of six joints; scape fully as long as the height of the head, contracted in diameter apically and very strongly so at the base; pedicel longer than thick; half as long as the first flagellar joint which is one-fourth longer than the second; third shorter, twice as long as thick; fourth clearly longer than wide, the following scarcely longer than wide and forming the club. Mesonotum rather sparsely and weakly punctate between the posteriorly converging, crenate parapsidal furrows, almost smooth laterally; scutellum nearly smooth, with very minute scattered punctures; with a coarse frenum behind, and anteriorly, except near the median line. Postscutellum arcuate, following the margin of the scutellum; of even width. Propodeum excavated to receive the abdominal horn, with a triangular tooth on each side of the excavation; its surface finely rugose. Abdominal petiole as long as wide, not very strongly narrowed basally, coarsely longitudinally striate over the entire upper surface, except near the lateral margins; basal horn or protuberance not conspicuously elevated and not filling the thoracic excavation in the normal position; second tergite striate on the basal third, coarsely and confluently punctate behind; following tergites similary punctate, but the punctures grow smaller on each succeeding segment; third tergite slightly longer than any of the others; sixth very short. Venter with the first sternite irregularly striate, the second rugoso-striate and the following each more sparsely punctate than the corresponding tergites. Tube of ovipositor heavily chitinized, consisting of three subequal sections, from the last of which issue three long hair-like bristles. Pleurae roughly sculptured, mainly rugose-reticulate, with the mesopleurae more or less obliquely striate. Propodeum deeply, irregularly rugose reticulate. Basal cell enclosed by indistinct veins; marginal vein twice as long as thick, more than half the length of the stigmal which is slightly curved and knobbed at apex; postmarginal vein long, extending halfway from the marginal to the apex of the wing; radial vein faintly indicated.

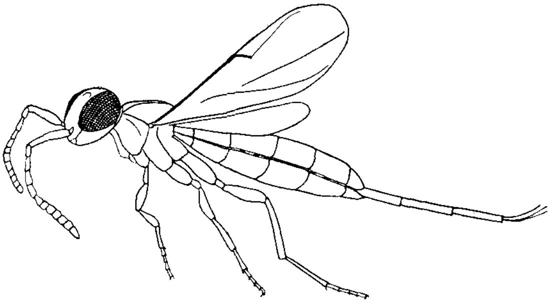

FIGURE 12. *Ceratoteleia caudata* Brues, ♀.

Type: Collection of the University of Königsberg, No. XIIIB937; no further specimens.

This is a very finely preserved specimen, showing practically the entire external structure. The extruded tubular ovipositor is very unusual, but probably does not represent any unique structure. However, this extrusion is not normally seen in specimens of this family nor in any other amber example.

Ceratoteleia succinophila sp. nov.

(Fig. 13)

♀. Length 3.4 mm. Apparently black, with the base of the antennae and the legs brownish or lighter; wings hyaline, with brown venation, the stigmal vein paler. Head globular. Front and vertex with moderately large, but not confluent punctures, on the occiput more or less finely rugose reticulate. Ocelli in a nearly equilateral triangle, the posterior ones almost contiguous to the eye margin. Sides of face, head behind the eyes and

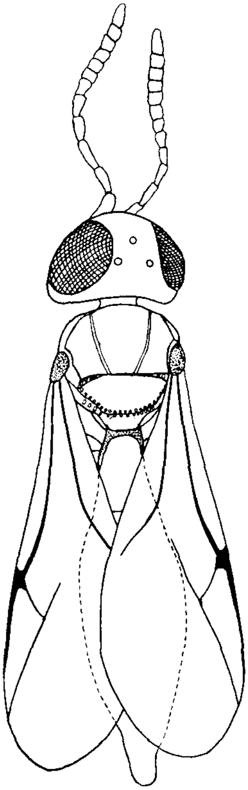

FIGURE 13. *Ceratoteleia succinophila* Brues, ♀.

malar space coarsely striate, the striae converging below as in *C. caudata*. Antennae long; with a moderately stout club of six joints, although the preceding joint is much thickened and might be considered as a seventh club-joint; scape not extending much above the middle of the face; pedicel more than twice as long as thick, about one-fourth shorter than the first flagellar joint which is one-half longer than the second; second and third of equal length, the third thicker; fourth shorter, but longer than thick; fifth and following about as long or barely longer than thick, the fifth narrower toward the base. Mesonotum and scutellum with moderate sized, well separated punctures; parapsidal furrows deep, weakly crenate, convergent behind and widened where they end at the base of the scutellum; base of scutellum margined at each side with a series of deep foveae which, however, do not extend to the median line; its posterior margin with a complete foveate or crenate line; postscutellum with a similar basal line at the sides, the median portion fully half as long as the scutellum, finely rugose. Petiole of abdomen striate; the striae extend to the base at the sides of the basal horn except medially at the extreme base where they are replaced by large punctures, the latter also extending backward between the striae to beyond the middle of this tergite; following tergites with moderately spaced punctures which grow much smaller toward the apex of the abdomen. Pleurae more or less irregularly rugoso-punctate, no distinct striated area on the mesopleura, its central oblique impression smooth. Basal cell in wings indicated by imperfectly formed veins; marginal vein very short, hardly longer than thick; stigmal vein, long, not distinctly knobbed at apex, nearly one-fifth as long as the submarginal; postmarginal vein very long, extending to the apical fourth of the faintly indicated radial cell.

Type in the Collection of the University of Königsberg.

Ceratoteleia proleptica sp. nov.

(Fig. 14)

♀. Length 3.6 mm. Black, including the legs in the type, but in other specimens the legs are ferruginous which may have been their color in life. Wings hyaline, the veins clear brown. Head coarsely, but not confluently punctate above and on the front; orbits below and cheeks coarsely and conspicuously striate as in the preceding two species. Antennal scape extending to the middle of the eye; pedicel two and one-half times as long as thick, one-fourth shorter than the first flagellar joint which is nearly one-half longer than the second; second and third equal; fourth shorter, much wider at apex than at base; first three club-joints each slightly wider than long. Posterior ocelli clearly separated from the eye-margin although close to it. Mesonotum strongly, closely punctate throughout, but not so coarsely on the parapsides; parapsidal furrows complete, noticeably convergent behind; scutellum sculptured like the mesonotum; postscutellum much less than one-half as long as the scutellum, its surface reticulate punctate or minutely rugose. Pleurae punctate reticulate; mesopleural furrow smooth, but above and behind it are distinct striae. Striae of first abdominal tergite not extending distinctly on to its basal half where they give way to reticulations that also extend posteriorly between the striae; second tergite less distinctly, more irregularly and more weakly striate; following tergites except the sixth also showing indications of striae. Marginal vein very short, almost punctiform; basal and radial veins not clearly indicated; stigmal vein long, faintly knobbed at the tip, less than one-fifth as long as the submarginal; postmarginal vein very

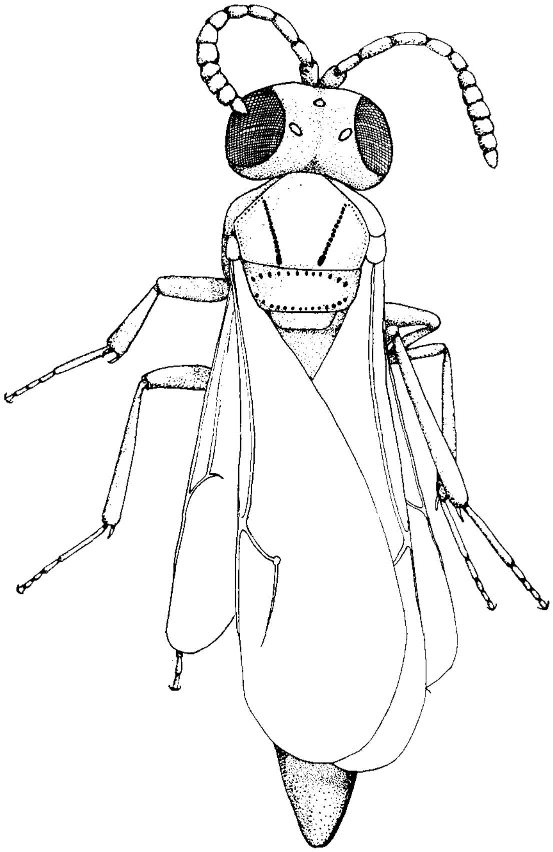

FIGURE 14. *Ceratoteleia proleptica* Brues, ♀.

long, extending nearly to the apex of the very faintly indicated radial cell.

Type: No. 8162, Museum of Comparative Zoology; paratype, No. 8163. Also numerous other additional specimens in this collection and that of the University of Königsberg. In all, there are 24 females that are clearly this species which is thus a very abundant one in the Baltic amber.

C. proleptica is undoubtedly related very closely to *C. succinophila,* but seems to be clearly distinct on the basis of the characters tabulated in the key.

Proplatyscelio gen. nov.

♀. Similar to Platyscelio Kieffer, but differing in having a long, well developed postmarginal vein in the wings. Head very much flattened, considerably wider than the thorax and apparently wider than high; posterior ocelli on the sharply rounded vertex, dividing the space between the eyes into three equal parts; occiput very short, strongly declivous, the temples very wide; eyes bare. Antennae 12-jointed, short; scape expanded apically, with the outer angle triangularly produced; club large, consisting of seven short joints. Prothorax very deeply excavated behind; mesonotum with complete parapsidal furrows; scutellum and propodeum of equal length, the latter with a median crenate groove, each one-half the length of the mesonotum. Abdomen flattened, somewhat narrower than the thorax and one-third longer than the head and thorax together. Wings ample, but not reaching the tip of the abdomen; submarginal vein extending beyond the middle of the wing, five times as long as the marginal vein which is longer than the stigmal; postmarginal vein long.

Type: *P. depressus* sp. nov.

Proplatyscelio depressus sp. nov.

(Fig. 15)

♀. Length 3.1 mm.; of wing 1.7 mm. Apparently entirely black or very dark in color, with hyaline wings. Head in front view broadly oval, with the eyes bulging laterally; face very wide, three times as wide as either eye; vertex sharply rounded, but not carinate above, the ocelli apparently in a very broad flat triangle, although the median one is not very clearly visible; surface of occiput finely and not very densely punctate; eyes not extending back on to the cheeks or temples. Mouthparts and sculpture of face not visible in the type. Antennae very short, not longer than the width of the head, attached close to the clypeus; scape triangularly expanded outwards at apex, curved at the base; the pedicel inserted at about the apical third of the scape; pedicel longer than thick, narrowed basally, much longer than the basal joint of flagellum which is as long as thick and narrowed basally; second flagellar joint quadrate, ones beyond transverse, more strongly so on the thicker part of the 7-jointed club. Pronotum very sharply, almost triangularly excavated behind, its anterior margin only slightly convex behind the neck-like front portion, so that the scapular region is quite wide; its surface closely, finely punctate. Mesonotum as wide as long, almost flat, its anterior margin defined by a sharply impressed groove that is irregularly transversely striate or crenate; parapsidal furrows slightly bowed inwards and more widely separated in front; surface entirely smooth, except the bottom of the parapsidal furrows which are finely granulate or punctate. Scutellum smooth, its anterior margin sinuate, the posterior one arcuate, no distinct groove at the basal margin. Propodeum

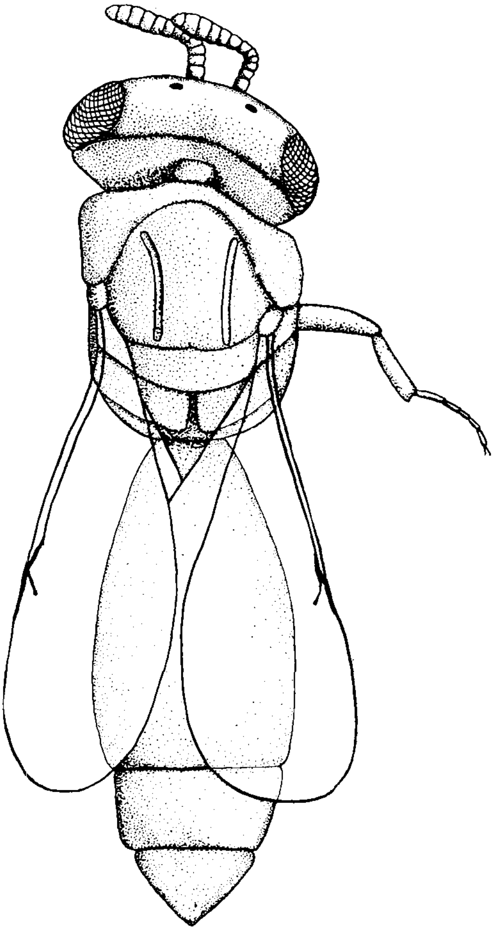

FIGURE 15. *Proplatyscelio depressus* Brues, ♀.

highly polished, only slightly declivous, with a median crenate furrow that expands behind into a small triangular rugulose median area at the base of the abdomen. Abdomen apparently smooth above, although it is concealed by the overlapping wings, except apically; seen from below nearly flat, as it is above, the segments of about equal length; lateral carinate edge unusually wide. Stigmal vein weakly clavate, about three-fourths as long as the marginal vein; postmarginal more than twice as long as the stigmal.

Type: In the University of Königsberg Collection (No. 4224, Phys. Oec. Ges).

This is a conspicuously flattened species which would fit perfectly in the modern genus Platyscelio, except for the long, fully developed postmarginal vein. Platyscelio is at present restricted to the Austromalayan region, whence a small number of species have been described.

Trachelopteron gen. nov.

(Fig. 16)

♂. Head, thorax and abdomen considerably flattened. Head attached to the thorax very close to the occipital line which is very slightly excavated; eyes small placed high up; ocelli forming a very low triangle or curved line, the lateral ones well removed from the eye-margin. Antennae 10-jointed; scape short, much expanded apically and excavated below to receive the large pedicel; first four flagellar joints extremely short, the first minute and very closely attached to the second; four club joints longer, but not much thicker. Pronotum visible as a narrow band of equal width; mesonotum flat, broader than long; without parapsidal furrows; separated from the broad, flat, short scutellum by a narrow, feebly impressed suture. Abdomen broad, little longer than the thorax; first segment very short, second nearly as long as the following ones together. Wings sharply bent upwards near the base so that they extend vertically above the body;[1] basal part of fore-wing narrow, strap-shaped; submarginal vein very short, with a curved apex probably representing a vestige of the stigmal vein; behind this with a thin vein, curved backwards at the tip and about as long as the submarginal vein, and further, with two broad, short thickenings joined basally at the anal angle; remainder of wing of normal size and form, without further venation. Legs short and stout.

Type: *T. angulipenne* sp. nov.

Trachelopteron angulipenne sp. nov.

(Fig. 16)

♂. Length 0.7 mm. Apparently black or piceous, including the legs; wings distinctly infuscated, the venation and thickenings dark brown. Head more than three times as wide as thick, quite flat between the base of the antennae and the ocelli; posterior ocelli almost as far from the eye as from the median line and well below the top of the head. Antennae very stout throughout, especially toward the apex where the last four joints form a more or less distinct club; nevertheless the specimen appears to be a male as the abdomen is blunt at the tip and shows the presence of seven tergites very clearly. The second to fourth flagellar joints are strongly transverse and the first is very short, rounded and much narrower than the others; the club joints increase in length apically, the penultimate one quadrate and the apical one about one-half longer than wide. Head, thorax and abdomen smooth and shining. Second tergite slightly wider than long; third to sixth subequal; seventh narrow, rounded at apex and slightly shorter.

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[1] This may be due to the process of inclusion in the amber, but both wings are bent in exactly the same way. This in connection with the unique thickenings at the base of the wing lead me to believe that the bending is not due to accident. I do not know of any similar modification in related forms, but in one common North American species of Encyrtidae (*Eupelmus rhizophilus* Ashm.) the wings are similarly bent sharply upward in the female which has greatly reduced wings.

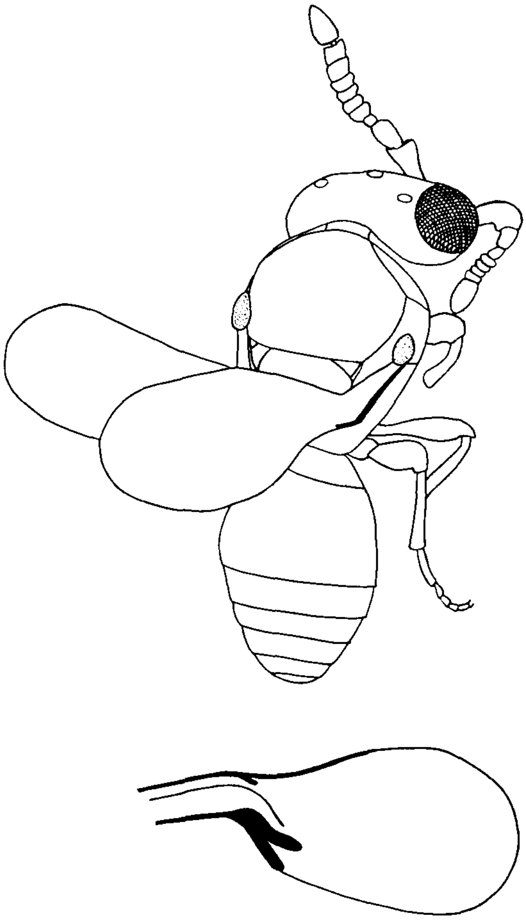

FIGURE 16. *Trachelopteron angulipenne* Brues. ♀ and wing of same.

Type: No. XIIIB922, University of Königsberg Collection.

I am quite at a loss as to where this peculiar insect should be placed. The body is strongly flattened, but not so much so as in scelionid genera like Platyscelio or Platytelenomus and the wings are very unusual, due to the adventitious vein-like thickenings. The antennae show a tendency to the double geniculation usually seen in the Platygastridae. The presence of a club-like thickening of the apical joints is noticeable in males of some genera of that family (*e. g.*, Sactogaster, Isostasius), although this in more exaggerated form is a typical female characteristic. The only known genus of Platygastridae with more than a simple clubbed submarginal vein is Proplatygaster, erected for a South American species by Kieffer, but this is evidently not a close relative of the present form. It is probable that the antennal scape will be found to be more widely expanded in the female as occurs in Sacespalus and other Indoaustralian genera.

A more exact placing of Trachelopteron must await the discovery of other related types.

Uroteleia gen. nov.

(Fig. 17)

♀. Head, in dorsal view, very thick, not much wider than long, the occiput emarginate and the anterior edge almost semicircular. Antennae 12-jointed; scape long and slender; pedicel and basal flagellar joints short, rounded; club elongate oval, six-jointed, the first club joint smaller than the others. Ocelli far removed from the occipital margin, the posterior ones close to the eye-margin. Prothorax long, its posterior edge nearly straight, transverse; mesonotum much wider than long, with deep parapsidal furrows; base of scutellum with a foveate groove, the posterior margin rounded. Abdomen greatly narrowed at the base, the first tergite small, as wide as long and about one-third the width of the third which is the widest; apical segments narrowed, the tip with a straight, tubular appendage, fully as long as the gaster, extending straight backwards. This is only partly sclerotized, composed of at least two telescoping segments, and about one-tenth as wide as long, with blunt tip. Submarginal vein extending beyond the middle of the wing; marginal vein thicker than the stigmal vein and shorter; postmarginal vein much longer than the marginal; no trace of a radial vein; basal vein present, at least the upper part near the submarginal vein.

Type: *U. synthetica* sp. nov.

This again is a type of doubtful affinities. The thinly chitinized, long tubular ovipositor has its counterpart in certain members of the Platygastridae, such as Gastrotrypes and at least one species of the large genus Platygaster.[2] Also an

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[2] These were described by the writer in 1922 in the

Australian genus (Stylaclista Dodd) of the family Belytidae is provided with a similar fleshy ovipositor as long as the gaster. The thick, rounded head of the present genus is quite similar to that of some Belytidae although not unknown in the Scelionidae (*e. g.*, Aratala Dodd) but the antennae are inserted lower on the face. Their exact insertion is slightly obscured in the amber, but in this important diagnostic character reference to the Belytidae cannot be made. The wing venation is, however, so typically that of the Scelioninae that I have placed it in this group although the head and the form of the abdominal petiole are reminiscent of the Belytidae.

Uroteleia synthetica sp. nov.

(Fig. 17)

♀. Length 1.25 mm.; abdominal tube 0.8 mm. Black, or dark colored, the funicle of the antennae paler; wings hyaline, slightly infuscated apically, with brown venation. Ocelli forming a triangle, the median one far below the level of the others. Eyes large; the face narrow above; the temples broad, obliquely narrowed behind the eyes and with a carinate posterior margin. Antennae with a large, heavy club; pedicel narrower than, and about as long as, the first flagellar joint, the latter narrowed at the base, slightly longer than thick; second to fourth flagellar joints rounded, not as large as the first and growing successively shorter; club as long as the remainder of the antenna, exclusive of the scape; its first joint small, abruptly widened to the apex; four following ones large, nearly one-half wider than long; the apical joint narrower, subtriangular, barely longer than the preceding one. Pro- and mesonotum smooth, impunctate, the latter strongly convex anteriorly, its furrows converging posteriorly. Metanotum and propodeum short, simple. Second abdominal tergite widened behind, its sides straight, the apical width twice that at the base; about as long as the third which is of even width and slightly wider than long; fourth tergite narrower; fifth very short and narrow; fleshy ovipositor including four telescoped segments, the first short, second longest, third shorter, the last but slightly projecting and rounded at apex. Marginal vein short, about twice as long as thick; stigmal vein strongly oblique, knobbed at the tip, a little longer than the marginal; postmarginal more than three times as long as the marginal.

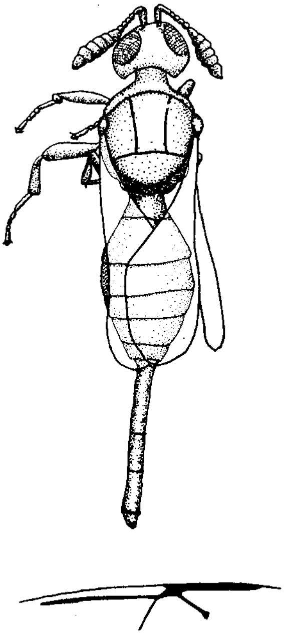

FIGURE 17. *Uroteleia synthetica* Brues, ♀ and stigmal area of wing.

Type: No. 61828B, in the University of Königsberg Museum. No other specimens.

Archaeoscelio gen. nov.

(Fig. 18)

Body very short, stout and roughly sculptured; antennae 14-jointed in both sexes, geniculate, with slender filiform flagellum in the male and with a thick, 10-jointed club in the female, inserted low on the face, near the large tridentate mandibles. Entire body both above and below very deeply, coarsely punctate, almost rugose. Head broad and rather thin, especially in the male, the face broad. Ocelli large, widely separated, in a low triangle. Pronotum very narrow medially, wider at the sides; mesonotum wider than long, without parapsidal furrows, its anterior margin nearly straight and oblique on the sides and sharply rounded medially; scutellum at the base with a deep frenum, its surface strongly convex, wider than long and fully half as long as the mesonotum. Legs rather slender, the femora and tibiae strongly clavate. Wing venation very unusual; submarginal (?) vein widely separated from the margin of the wing, giving off a short vein or thickening at its end to the costal margin and forking just

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Proceedings of the American Academy of Arts and Sciences, vol. 57, pp. 263–283, but have unfortunately been omitted by Kieffer in his compilation on the family Scelionidae in 1926 (Das Tierreich, Lief. 48).

beyond the posterior branch, forming a stigmal vein from the end of which a weaker vein extends toward the wing-tip to enclose a quite clearly formed and nearly complete radial cell.

Type: *A. rugosus* sp. nov.

Archaeoscelio rugosus sp. nov.

(Fig. 18)

♂. Length 2.3 mm. Apparently entirely black, with the wings slightly infuscated, especially near the veins which are brown. Head nearly three times as wide as long in dorsal view; ocelli large, the posterior pair twice as far from one another as from the eye margin, forming with the anterior one a very low triangle. Surface of head anteriorly coarsely, closely punctate, behind the ocelli rugose-reticolate. Temples and cheeks strongly carinate along the posterior edge, the malar space half as long as the eye, without furrow; eye nearly twice as high as wide. Mandibles very wide at the base, terminating in three strong teeth. Scape of antenna reaching to the middle of the eye, cylindrical and much thickened toward apex; pedicel small, elongate, as long as the thickness of the scape. Flagellum slightly thickened toward the middle; first joint one-half longer than wide, narrowed basally; second about as long as the first, the ones beyond shorter, subequal, clearly longer than wide, the last longer and pointed. Thorax above deeply punctate, less coarsely so on the pronotum and becoming quite rugose on the mesonotum behind and on the scutellum, the latter with two distinct, blunt teeth at its tip. Upper side of abdomen hidden by the wings above, but seen from the side seven or eight tergites are visible, the second and third longest, but greatly exceeding the fourth and fifth, the apical ones growing much shorter; the surface of the tergites appears to be coarsely longitudinally rugose. The venter shows the third (second visible) sternite to be only about half the length of the second; third and following with a basal row of pits separated by short longitudinal carinae. The venter as well as the dorsum is expanded so that the sclerites are widely separated by the connecting membrane, but this condition is undoubtedly due to an internal expansion of gases before the amber hardened, and lengthens the abdomen considerably in the specimen.

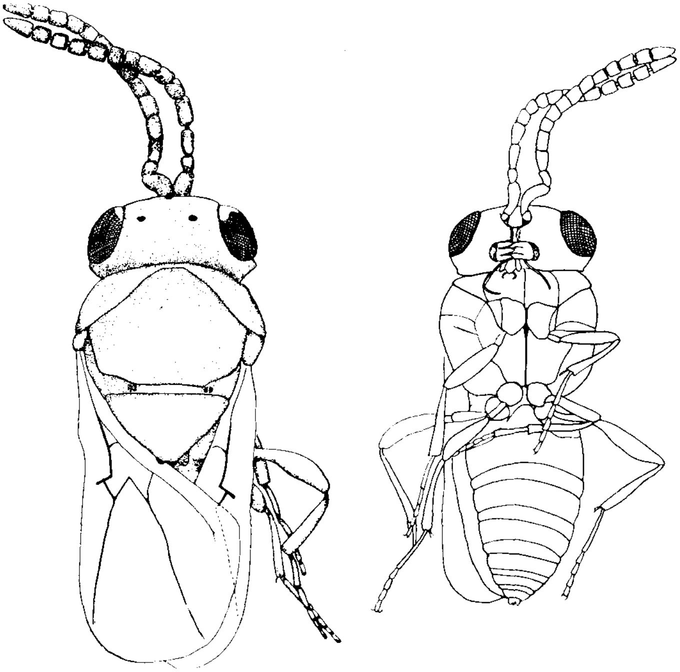

FIGURE 18. *Archaeoscelio rugosus* Brues, ♀ in dorsal and ventral view.

♀. Length 1.9 mm. Abdomen no longer than the thorax, the sclerites all closely connected the upper surface appearing to form a sort of heavy carapace composed of six tergites decreasing in length from the basal one to the sixth. Antennal scape shorter and thicker than in the male and not narrowed basally; pedicel and first flagellar joint as in the male; second flagellar joint shorter and much thicker than the first, about as long as wide at apex; following joints forming a long club with each joint transverse, those near the middle of the club especially so, these being fully twice as wide as long. Whole body even more coarsely sculptured than in the male, the eye shorter and the malar space longer.

Type: ♂. No. XIIIB929, in the collection of the Königsberg Museum. Allotype, ♀, in the Museum of Comparative Zoology, No. 8164.

Archaeoscelio filicornis sp. nov.

♂. Length 1.2 mm. Very similar to the preceding species, but with the antennae very much more slender, the flagellar joints all at least twice as long as thick. Ocelli forming a nearly equilateral triangle, the posterior ones as far from the eye as from one another. Head rather shallowly sculptured above and on the face, the malar space quite smooth, with a distinct furrow. Scutellum rounded at apex, without teeth.

Type: No. 8165, Museum of Comparative Zoology.

This species is clearly very closely related to *A. rugosus* which it resembles almost exactly, except for the very striking differences noted above. It is unfortunately not well preserved and the wings are not in a position to be examined.

It is with some misgivings that I have included in this family the very anomalous insects just described, although it seems impossible to place them elsewhere. The most striking discrepancy is the presence of fourteen joints in the antennae of both sexes which are otherwise as in other Scelionidae with long scape, filiform flagellum (♂), clubbed flagellum (♀) and no ring joints discernible in either sex. One other fossil genus which I described recently from Canadian amber as Proteroscelio has likewise 14-jointed antennae, but they are flattened, as is the whole body, like the recent Platyscelio and the Oligocene Proplatyscelio described earlier in this paper. The general habitus, including the large, tridentate mandibles, reminds one of a chalcidoid, but there is no trace of ring-joints in the antennae and the morphology of the thoracic dorsum does not conform to that seen in the Chalcidoidea. The very coarsely sculptured body, with the head so completely fitted to the thorax both above and below is very striking, but finds its counterpart occasionally in several groups of Hymenoptera. Likewise, the wing venation is not in close conformity with that of any group known to me. The presence of two clearly distinct species in such an aberrant genus is most unexpected and suggests the prevalence of insects related to them in the early Tertiary.

Proceedings of the American Academy of Arts and Sciences

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RECORDS OF MEETINGS, 1938–1939, 1939–1940

BIOGRAPHICAL NOTICES

PRESIDENTS OF THE ACADEMY

OFFICERS AND COMMITTEES FOR 1940–1941

LIST OF THE FELLOWS AND FOREIGN HONORARY MEMBERS

STATUTES AND STANDING VOTES

RUMFORD PREMIUM

PERMANENT SCIENCE FUND

RECORDS OF MEETINGS

One Thousand Two Hundred and Forty Eighth Meeting

OCTOBER 19, 1938—STATED MEETING

The Academy met at its House at 8.35 P. M.

The President in the Chair.

There were present sixty-one Fellows and seven guests.

The records of the meeting of May 11 were read and approved.

The Fellows elected in May were then presented to the Academy.

The Corresponding Secretary reported the receipt of letters from the Societas Scientiarum Fennica, the Franklin Institute and Greensboro College expressing appreciation of the Academy's sending delegates or greetings to their celebrations.

He also announced that the President had appointed the following delegates:

Professors H. B. Phillips and Philip Franklin to the Semicentennial Celebration of the American Mathematical Society, at New York City, on September 6–9, 1938;

President D. C. Jackson to the Installation of Edwin Sharp Burdell as Director of Cooper Union, New York City, on November 3;

Dr. A. C. Lane to the Inauguration of Leonard Carmichael as President of Tufts College, on November 4.

It was also reported that the following invitations had been received, to which the Academy had responded by sending greetings:

Semi-Centennial Celebration of Utah State Agricultural College, Logan, June 5–7, 1938;

Inauguration of Charles Burgess Ketcham as President of Mount Union College, Alliance, Ohio, October 20, 1938;

Inauguration of William Harold Cowley as President of Hamilton College, Clinton, N. Y., October 29, 1938.

The Corresponding Secretary reported the receipt of a letter resigning Fellowship from Morris B. Lambie, and of one resigning membership in the Council from Lawrence J. Henderson, which had been accepted with regret.

He announced that the Council had made the following grants from the Permanent Science Fund:

1. To Prof. D. C. Carpenter, New York State Experiment Station, Geneva, $300, toward the purchase of optical equipment for an investigation of the effect of neutral salts on amino acids and proteins.
2. To Dr. V. I. Cheadle, Instructor in Botany, Rhode Island State College, Kingston, $300, toward the cost of technical assistance in the preparation of material for the study of the conductive system in a group of the Monocotyledonae.
3. To Dr. S. R. Gifford, Northwestern University Medical School, Chicago, $500, toward the cost of technical assistance in a study of the relation of the physical change of protein molecules in cataract of the eye.
4. To Prof. W. L. Gilliland, University of Maine, Orono, $250, toward the purchase of precision equipment for use in studying certain equilibria in Grignard reagents.
5. To Prof. F. L. Humoller, Loyola University School of Medicine, Chicago, $400, toward the cost of animals and materials in a study of the chemistry of a toxic fraction prepared from Salmonella enteritidis.
6. To Dr. Valy Menkin, instructor in Pathology, Harvard Medical School, Boston, $500, toward the cost of an investigation of the nitrogenous substances in areas of injury.
7. To Prof. Gregory Pincus, Clark University, Worcester, $800, for technical assistance and supplies in the further study of the development of artificially activated mammalian ova *in vivo* and *in vitro*.
8. To Prof. G. W. Prescott, Albion College, Albion, Mich., $175, toward the expenses of an investigation of phytoplankton in the Panama Canal Zone.
9. To Prof. Christianna Smith, Mount Holyoke College, South Hadley, $200, for the purchase of animals in a study of the origin and differentiation of red blood corpuscles.
10. To Dr. Oswald Tippo, Instructor in Botany, University of Illinois, Urbana, $75, for

the cost of text figures necessary for the effective publication of a monograph on the Moraceae.

11. To Prof. Dorothy W. Weeks, Wilson College, Chambersburg, Pa., $500, for technical assistance in extension of the analysis of the spectrum emitted by neutral iron atoms.

The Corresponding Secretary announced the receipt of letters accepting election as Fellows from Henry Moore Bates, Marland Pratt Billings, Julius Seelye Bixler, Emile Monnin Chamot, James Pyle Wickersham Crawford, Edmund Ezra Day, Alfred Victor de Forest, Robert Gray Dodge, John Charles Duncan, Allyn Bailey Forbes, Horace Sayford Ford, James Everett Frame, Claude Moore Fuess, Frank Washburn Grinnell, Robert Casad Hockett, Joseph Hudnut, E. Morton Jellinek, Melvin Maynard Johnson, Howard Mumford Jones, James McCauley Landis, John Moyes Lessells, Stewart Mitchell, James Madison Morton, Hyder Edward Rollins, Bernadotte Everly Schmitt, Charles Seymour, Kenneth Vivian Thimann, Harold Clayton Urey, Bentley Wirt Warren, Thomas North Whitehead, Grenville Lindall Winthrop, George Bernays Wislocki; and of letters accepting Foreign Honorary Membership from Edgar Douglas Adrian, Dionisio Anzilotti, Sir Joseph Barcroft, William Warwick Buckland, Mircea Djuvara, Emmanuel Fauré-Frémiet, Arthur Lehman Goodhart, Rt. Hon. Lord Macmillan, Leopold Ruzicka, Nevil Vincent Sidgwick, Kenzo Takayanagi, Georges Urbain, Rt. Hon. Lord Wright; also a letter from Henry Sloane Coffin declining Fellowship.

The President announced the death of eleven Fellows: Ernest William Brown (Class I, Section 1), William Wallace Campbell (Class I, Section 1), Benjamin Nathan Cardozo (Class III, Section 1), Thomas Hovey Gage (Class III, Section 1), Nathaniel Thayer Kidder (Class III, Section 4), Elmer Peter Kohler (Class I, Section 3), Andrew James Peters (Class III, Section 4), Arthur Prentice Rugg (Class III, Section 1), Edmund C. Tarbell (Class IV, Section 4), Frank Bursley Taylor (Class II, Section 1), Owen Wister (Class IV, Section 4); and of one Foreign Honorary Member: Joseph Bédier (Class IV, Section 3).

The following communication was presented:

Mr. George Howard Parker: "Modern Views on the Action of the Nervous System as Illustrated by the Color Changes of Animals," illustrated with lantern slides.

Four papers were read by title: "Chang Po-Tuan of T'ieu T'ai, his Wu Chên P'ieu, Essay on the Understanding of the Truth," by T. L. Davis and Chao Yün-Ts'ung; "Gyromagnetic Ratios for Ferromagnetic Substances: New Determinations and a New Discussion of Earlier Determinations," by S. J. Barnett; "Some Physical Constants of a Few Hydrocarbons and their Structural Isomers," by M. Wojiciechowski, presented by F. G. Keyes; "Interatomic Forces and Helium in Rocks," by N. B. Keevil, presented by R. A. Daly.

The meeting was dissolved at 9.45 P. M.

One Thousand Two Hundred and Forty Ninth Meeting

November 9, 1938—Stated Meeting

The Academy met at its House at 8.30 P. M.

The President in the Chair.

There were present forty-nine Fellows and five guests.

The records of the meeting of October 19 were read and approved.

The Corresponding Secretary announced the appointment of Professor Tenney L. Davis to fill out the unexpired term on the Council of Professor L. J. Henderson.

He also announced his own resignation as Corresponding Secretary and the appointment of Professor Abbott P. Usher to fill out his term.

He reported that the Council had reappointed Professor J. D. M. Ford for four years as a delegate from the Academy to the American Council of Learned Societies.

The Corresponding Secretary reported the receipt of letters accepting Fellowship from Richmond Laurin Hawkins and William Morton Prest, and a letter from Professor Ulrich Wilcken, of Berlin, expressing regret that he had been refused official permission to accept his election as a Foreign Honorary Member of the Academy.

He also reported the receipt of a letter from Hamilton College expressing appreciation for the greetings sent by the Academy on the occasion of President Cowley's inauguration.

The President expressed regret for the resignation of Professor Leigh Hoadley as Corresponding Secretary, made necessary by his absence from the country during the next few months.

The President announced the death of Maurice d'Ocagne, Foreign Honorary Member in Class I, Section 4.

The following communication was presented:

Mr. George Sarton: "The Function of Academies—Past and Present."

The meeting was dissolved at ten P. M.

One Thousand Two Hundred and Fiftieth Meeting

DECEMBER 14, 1938—STATED MEETING

The Academy met at its House at 8.25 P. M.

The President in the Chair.

There were present thirty-one Fellows and nineteen guests.

The records of the meeting of November 9 were read and approved.

The Corresponding Secretary reported that the Council had approved the following proposed amendments to the Statutes, which had been recommended by the Special Committee on Academy Policy:

1. Addition to Chapter II, Article 5, after Paragraph 2: "Fellows resident outside fifty miles of Boston shall pay annual dues of five dollars, which shall entitle them to all the privileges of resident Fellows."

2. Delete Chapter XII, Article 5, which now reads: "No Fellow shall introduce a guest at any meeting of the Academy until after the business has been transacted, and especially until after the result of the balloting upon nominations has been declared."

After some discussion of the first proposed amendment, it was *Voted* to lay it on the table until the next meeting.

The motion to adopt the second amendment was carried unanimously.

The President announced the following deaths: Edward Murray East (Class II, Section 2), Edwin Herbert Hall (Class I, Section 2), William McDougall (Class IV, Section 1), George Burgess Magrath (Class II, Section 4), Charles Edward Munroe (Class I, Section 3), John Charles Phillips (Class II, Section 3), and Georges Urbain, Foreign Honorary Member in Class I, Section 3.

The following communication was presented:

Mr. Hudson Hoagland: "Some Aspects of Electrical Brain Waves," with lantern illustrations.

The meeting was dissolved at 10 P. M.

One Thousand Two Hundred and Fifty First Meeting

JANUARY 11, 1939—STATED MEETING

The Academy met at its House at 8.25 P. M.

The President in the Chair.

There were present forty-seven Fellows and ten guests.

The records of the meeting of December 14 were read and approved.

The Corresponding Secretary reported that the Council had voted to recommend to the Academy an amendment to the Statutes which would provide for a Standing Committee on Resources, to be made part of the order of business at the next meeting.

The President announced the death of William MacDonald, Fellow in Class III, Section 2.

The proposed amendment to the Statutes requiring that Fellows residing more than fifty miles from Boston should pay annual dues of five dollars was then brought before the Academy.

An amendment to this amendment was proposed that all future Fellows residing more than fifty miles from Boston shall be so charged, but that present Fellows of this group be exempted.

After some discussion this amendment to the proposed amendment was voted.

A ballot was then taken on the original amendment as amended, *i. e.*, Fellows residing more than fifty miles from Boston elected after 1938 shall, and other non-resident Fellows may, pay annual dues of five dollars, which shall entitle them to all privileges of resident Fellows.

This was affirmatively voted by a ballot of thirty-five to ten.

The following communication was presented:

Dr. Alexander Forbes: "Aerial Photography and Map Making," illustrated with lantern slides.

The meeting was dissolved at 10.10 P. M.

One Thousand Two Hundred and Fifty Second Meeting

FEBRUARY 8, 1939—STATED MEETING

The Academy met at its House at 8.25 P. M.

The President in the Chair.

There were present thirty-five Fellows and four guests.

In the absence of the Recording Secretary Mr. Tenney L. Davis was asked to assume his duties.

The records of the meeting of January 11 were read and approved.

The President announced the death of four Fellows: Fabian Franklin (Class I, Section 1), Edward Sapir (Class IV, Section 2), Albert Sauveur (Class I, Section 4) and Frank Edward Winsor (Class I, Section 4).

It was *Voted*, that the Committee on Policy is authorized to recommend changes in the Statutes establishing a Committee on Resources.

The following communication was presented: Mr. Charles M. Spofford: "Contribution on the Development of Bridges and Similar Structures from Ancient Times, with Consideration of the Religious, Political, Artistic, Scientific and Economical Factors which have Influenced their Construction," illustrated with lantern slides.

The meeting was dissolved at 10.15 P. M.

One Thousand Two Hundred and Fifty Third Meeting

MARCH 8, 1939—STATED MEETING

The Academy met at its House at 8.30 P. M.

The President in the Chair.

This meeting having been designated as Ladies' Night, there were present about 150 Fellows and guests.

In the absence of the Recording Secretary the reading of the records of the meeting of February 8 was omitted.

On the recommendation of the Council the following appropriations were voted for the ensuing year:

From the income of the General Fund, $7,200, to be used as follows:

for General and Meeting expenses	$ 900
for Library expenses	2,100
for Books, Periodicals, and Binding	1,200
for House expenses	2,000
for Treasurer's expenses	900
for President's expenses	100
	$7,200

From the income of the Publication Fund, $3,000, to be used for publication.

From the income of the Rumford Fund, $2,800, to be used as follows:

for Research	$2,000
for use at the discretion of the Committee	800
	$2,800

From the income of the C. M. Warren Fund, $900, to be used at the discretion of the Committee.

The Corresponding Secretary read a letter resigning Fellowship from Associate Justice Felix Frankfurter; also a letter of acceptance of Foreign Honorary Membership from Dr. Heinrich Brüning.

The President announced the death of two Fellows: Herbert Parker (Class III, Section 1) and Edmund Beecher Wilson (Class II, Section 3); and one Foreign Honorary Member: Sören Peter Lauritz Sörensen (Class I, Section 3).

The President announced that the following Fellows were appointed to serve as a Nominating Committee:

Tenney L. Davis, of Class I
S. Burt Wolbach, of Class II
Ralph E. Freeman, of Class III
Walter E. Clark, of Class IV

The President introduced the speaker of the evening, Mr. S. Foster Damon, of Brown University, who read a poem from manuscript, "The Fatigue of Burgwine."

The meeting was dissolved at 9.45 P. M.

One Thousand Two Hundred and Fifty Fourth Meeting

APRIL 12, 1939—STATED MEETING

The Academy met at its House at 8.23 P. M.

The President in the Chair.

There were present sixty-seven Fellows and seven guests.

The records of the meetings of February 8 and March 8 were read and approved.

The Corresponding Secretary announced that the Council had made the following grants from the Permanent Science Fund:

1. To Professor Emil Bozler, of the Department of Physiology, Ohio State University, for the purchase of apparatus to be used in a study of action potentials of smooth muscle, $250.

2. To Dr. Donald E. Cameron, Professor of Neurology and Psychiatry, Albany Medical College, for the purchase or construction of apparatus, as specified, to study the change in response to repetition of an unpleasant situation in psychotic patients, $200.

3. To Professor William H. Cole, Department of Physiology and Biochemistry, Rutgers University, for technical assistance, materials and

special apparatus for the determination of the chemical composition of the bloods of invertebrates, $500.

4. To Professor Robert S. Harris, Department of Biology, Massachusetts Institute of Technology, for the purchase of a newly developed instrument for optical quantitation of Vitamin B_1, for a study of the daily requirement of young and adult individuals in respect to this vitamin, $400.

5. To Dr. Caryl P. Haskins, Union College, Schenectady, N. Y., to aid in the construction of apparatus for studying the effects of proton bombardment of spores, $500.

6. To Professor Charles E. Lane, University of Wichita, Kansas, for technical assistance and materials in a study in the relationship between the pituitary, the ovary, and the estrous cycle in rats, $300.

7. To Mr. Karl O. Lange, Research Meteorologist, Blue Hill Observatory, to aid in the construction and testing of automatic radio transmission of meteorological records to a central station, $300.

8. To Professor William J. Luyten, Department of Astronomy, University of Minnesota, as an aid in securing a supervisor for student measurements in his study of the proper motions of stars in the southern hemisphere, $500.

9. To Professor Hugh M. Raup, Harvard University, as a contribution towards general field expenses of a botanical survey of the southwestern part of the District of Mackenzie, contingent upon his securing necessary funds to assure the trip in the summer of 1939, $400.

10. To Professor Kenneth A. Siler, Department of Physiology and Pharmacology, University of Arkansas School of Medicine, for the purchase or construction of necessary instruments in an investigation of the blood flow of the coronary system, $250.

The President announced the death of Tenney Frank, Fellow in Class IV, Section 3.

The following amendments to the Statutes recommended by the Council were passed by a unanimous vote:

Chapter II, Article 6. Instead of "one copy of all Publications of the Academy" substitute "one copy of all numbers of the Proceedings and Memoirs of the Academy which have been issued," etc.

Chapter II, Article 7. Strike out the words "on request."

Chapter III. In the paragraph, "Notice shall be sent," etc., substitute "first" for "fifteenth" of February. After this paragraph insert the paragraph, "The Corresponding Secretary shall, on the second of February, transmit to the several Vice-Presidents the nominations for Fellows and Foreign Honorary Members in their respective classes. Each Class Committee shall, before the sixteenth of February, consider the nominations, and may add others for the purpose of securing proper membership in the Academy, to the end that those in the country of highest distinction in their several classes may be Fellows."

Chapter IV, Article 1, paragraph 3, to be amended to read as follows: "The Councillors, with the officers previously named and the Chairmen of the House Committee and the Committee on Resources and Policy, *ex officio*, shall constitute the Council."

Chapter IX. Add to Article 1, "The Editor shall select as Associate Editor one member of the Committee of Publication, and the Associate Editor shall assist the Editor in the duties of his office in such way as the two shall find most convenient."

Change Article 2 to read, "In conjunction with the Committee of Publication, the Editor," etc.

Chapter X. Remove Article 7 from this place, and add it to Section ix of Article 2 of Chapter XI, this Section to be re-numbered x. Renumber Article 8 of Chapter X accordingly.

Chapter XI. Insert a new Section ii in Article 2, and re-number the other sections accordingly. New Section ii, "*The Committee on Policy and Resources* to consist of five Fellows and the President, *ex officio*, one of the five elected members to be elected each year to serve for a term of five years, except that the five elected in 1939 shall be elected for terms of one, two, three, four, and five years respectively, the Committee to concern itself with procuring funds for the Academy, to study the activities and needs of the Academy, and to recommend, for the approval of the Council, means by which the functions and purposes of the Academy may best be fulfilled."

Article 2, Section iv, re-numbered v, change to read, "but Fellows may be supplied at half price with volumes and with single publications which they are not entitled to receive gratis."

Article 2, Section ix, re-numbered x, strike out "six in 1933."

Chapter XII, Article 1. Strike out last paragraph and insert the following, "The Council shall have authority, as occasion may demand, to arrange additional meetings and to cancel any of the Statutory meetings, except that meetings for transacting business shall be held as required by the Statutes."

Article 5. Strike out and substitute, "Fellows may introduce guests at any of the literary or scientific meetings of the Academy."

Standing Votes. Strike out all of Section 4 and re-number accordingly.

The Communication consisted of a Symposium on "What Constitutes Social Progress," by Messrs. L. J. Henderson, C. C. Brinton, and E. B. Wilson.

The meeting was dissolved at 10.10 P. M.

One Thousand Two Hundred and Fifty Fifth Meeting

MAY 10, 1939—ANNUAL MEETING

The Academy met at its House at 8.20 P. M.

The President in the Chair.

There were present forty-two Fellows and one Foreign Honorary Member.

The records of the meeting of April 12 were read and approved.

The Corresponding Secretary announced the appointment by the Council of the two following committees for the ensuing year:

Amory Fund Committee: Messrs. Roger I. Lee, *Chairman*, Walter B. Cannon, David Cheever, Leigh Hoadley, Edward E. Tyzzer, Soma Weiss.

Permanent Science Fund Committee: Messrs. John W. M. Bunker, *Chairman*, George R. Agassiz, Gregory P. Baxter, Charles T. Brues, Hudson Hoagland, Edwin B. Wilson, S. Burt Wolbach.

The President announced the death of three Fellows: Henry Fay (Class I, Section 3), William Ebenezer Ford (Class II, Section 1), and Jacob Goodale Lipman (Class II, Section 2).

The following report of the Council was presented:

REPORT OF THE COUNCIL

Since the last report of the Council there have been reported the deaths of twenty-eight Fellows: Ernest William Brown, William Wallace Campbell, Benjamin Nathan Cardozo, Edward Murray East, Henry Fay, William Ebenezer Ford, Tenney Frank, Fabian Franklin, Thomas Henry Gage, Edwin Herbert Hall, Nathaniel Thayer Kidder, Elmer Peter Kohler, Jacob Goodale Lipman, William MacDonald, William McDougall, George Burgess Magrath, Charles Edward Munroe, Herbert Parker, Andrew James Peters, John Charles Phillips, Arthur Prentice Rugg, Edward Sapir, Albert Sauveur, Edmund C. Tarbell, Frank Bursley Taylor, Edmund Beecher Wilson, Frank Edward Winsor, Owen Wister; and four Foreign Honorary Members: Joseph Bédier, Maurice d'Ocagne, Sören Peter Lauritz Sörensen, Georges Urbain.

Thirty-seven Fellows and sixteen Foreign Honorary Members were elected by the Council and announced to the Academy in May 1938.

The roll now includes 767 Fellows and 122 Foreign Honorary Members (not including those elected in May 1939).

The annual report of the Treasurer, Horace S. Ford, was read, of which the following is an abstract:

GENERAL FUND

Receipts

Income on hand April 1, 1938		$ 1,166.00
Investments	$ 2,774.97	
Special Contributions	285.00	
Assessments and Admissions	4,280.00	7,339.97
		$ 8,505.97

Expenditures

Expenses of Library		$ 2,071.00
Books and Binding		1,590.19
General Expenses	$ 1,181.87	
Less Meetings Credits	84.75	
		1,097.12
House Expenses	$ 2,400.16	
Less Meetings Credits	240.00	
		2,160.16
President's Expenses		39.00
Treasurer's Expenses	$ 1,046.96	
Less Insurance Refund	66.87	980.09
		$ 7,937.56
Income Transferred to Principal		335.00
Accrued Interest Paid		22.38
		$ 8,294.94

Rumford Fund

Receipts

Income on hand April 1, 1938	$ 401.18
Investments	2,951.62
	$ 3,352.80

Expenditures

Research Awards, etc.		$ 1,707.00
Medal (Dr. Compton)		513.06
		$ 2,220.06
Less Receipts:		
Camera Sale	$ 30.00	
Insurance (Compton Medal)	537.06	
Harvard University (Rumford Memorial)	7.50	574.56
		$ 1,645.50
Income Transferred to Principal		143.00
Accrued Interest Paid		286.34
		$ 2,074.84

C. M. Warren Fund

Receipts

Income on hand April 1, 1938	$ 290.74
Investments	963.35
	$ 1,254.09

Expenditures

Research Awards	$ 850.00
Income Transferred to Principal	47.50
	$ 897.50

Publication Funds

Receipts

Income on hand April 1, 1938		$ 3,827.65
Appleton Investments	$ 985.98	
Centennial Investments	1,702.30	
Publication Sales, etc.	408.74	
Contribution	10.00	
Hatch Publication Fund	500.00	
Lake Fund Subscriptions	858.55	4,465.57
		$ 8,293.22

Expenditures

Publications—General	$ 2,107.62	
Publications—Lake	2,006.59	
		$ 4,114.21
Income Transferred to Principal		121.00
Accrued Interest Paid		42.90
		$ 4,278.11

Francis Amory Fund

Receipts

Income on hand April 1, 1938	$10,706.93
Investments	2,309.00
	$13,015.93

Expenditures

Publishing Statement	$ 73.10

Permanent Science Fund

Receipts

Income on hand April 1, 1938	$ 1,725.00
From Trustees	11,891.25
	$13,616.25

Expenditures

Grants	$13,304.00
Expenses	77.25
	$13,381.25

The following reports were also presented:

Report of the Library Committee

During the year 110 volumes and 33 unbound numbers of serials have been borrowed by 15 Fellows and 18 libraries, and many more have been consulted at the Academy.

The number of volumes on the shelves at the time of the last report was 45,580. During the year 459 volumes were added, making the number now 46,039. Of this 459 volumes, 383 were received by gift or exchange and 76 were purchased.

The following sum was placed at the disposal of the Librarian this year:

Balance from previous year	$ 388.23
Appropriation	3,300.00
Total	$3,688.23

The expenses charged to the Library account during the financial year ending March 31, 1939, were:

Salaries	$2,066.00
Binding	964.50
Purchase of Books and Periodicals	625.69
Miscellaneous library expenses	5.00
Total	$3,661.19

Last year I reported that the Library Committee had cancelled the subscriptions to several scientific journals in an effort to reduce the Library budget. I am happy to say that we are continuing to receive one of these, the Journal of Morphology, through the kindness of Mr. George Howard Parker.

At present we are subscribing to 40 scientific journals, and are receiving by gifts or in exchange for the Academy's Proceedings and Memoirs 800 serial publications of academies and other learned societies in North and South America, Europe, Africa, Asia, Australia and New Zealand, several of which are not to be found in any other library in Boston or Cambridge.

Respectfully submitted,
H. W. Shimer, *Librarian*

May 10, 1939.

Report of the Rumford Committee

The Rumford Committee of the American Academy of Arts and Sciences has held two meetings during the year—one on April 11, 1938, and the other on January 19, 1939. At these meetings and by correspondence the members of the committee have voted the following grants:

No. 342 to	Dr. Clarence Zener for the purchase of an oscillator to be used in experiments on "the connection of internal friction in solids and thermal conductivity"	$ 385
No. 343 to	Dr. T. E. Sterne, Dr. R. M. Emberson, and R. Loevinger to cover a part of the expenses of the construction of automatic recording apparatus for the radiometer attached to the Wyeth reflector at Oak Ridge, Harvard, Massachusetts	290
No. 344 to	Professor Frances G. Wick, Vassar College, to assist in the purchase of a spectrometer for the study of luminescence	400
No. 345 to	Professor Francis Birch, Harvard University, for the study of the effect of stress upon the thermal conductivity of rocks and other materials of geological interest	400
No. 346 to	Dr. G. Z. Dimitroff and H. W. French of Harvard for assistance in the development of the electron multiplier and amplifier for measurement of faint sources of light	250
No. 347 to	W. M. Powell of Kenyon College for special studies in radiation	175
	Total	$1,900

At the meeting on January 19 the first vote on the awarding of the Rumford Medal to Professor George R. Harrison of Massachusetts Institute of Technology was taken. A confirming vote was taken by correspondence in February.

Harlow Shapley, *Chairman*

Report of the C. M. Warren Committee

The Committee had at its disposal during the fiscal year 1938–1939 $1,115.84, of which $850 was appropriated to aid scientific investigations.

Since the last annual report grants have been made as follows:

Professor Francis Bitter, Massachusetts Institute of Technology, $200, for the purchase of a special balance to be used in the investigation of the chemical equilibrium of alloys.

Professor Arthur F. Scott, Reed College, $200, for the purchase of a special balance to be used in the determination of the atomic weights of beryllium and fluorine.

Professor C. R. Johnson, University of Texas, $100, to be used for the purchase of apparatus required in the determination of atomic weights.

Professor Robert C. Hockett, Massachusetts Institute of Technology, $200, to be used in the preparation of certain compounds needed in the synthesis of new sugars.

Doctor William F. Ross, Radcliffe College, $150, to be used, with other grants, for the purchase of a super centrifuge required in the further study of the chemistry of hemoglobin.

Reports of progress have been received from Messrs. Huntress, Johnson, Kirk, Schmidt and Schmid.

The papers listed below, which have not been previously reported, describe the results of investigations aided by the Warren Fund.

Frederic C. Schmidt, Frank J. Studer and Joseph Sottysiak. "Heats of Solution and Heats of Reaction in Liquid Ammonia. V. The Alkali and Alkaline Earth Metals." J. Am. Chem. Soc., *60*, 2780 (1938).

Hermann Schmid, "Katalysen der Diazotierung." Angewandte Chemie, *50*, 615 (1937).

James F. Norris, *Chairman*

May 10, 1939.

REPORT OF THE COMMITTEE OF PUBLICATION

Six numbers of the Proceedings and two Fasciculi of the "Monumenta Palaeographica Vetera" have been published this year. The latter series now lacks one Fasciculus of those originally projected. Two numbers of Proceedings and one number of the Memoirs are in press.

The change to a larger format for the Proceedings, although it has, at first, increased the difficulties of preparation of manuscript for the press, has also justified itself from the financial point of view.

The balances shown below reflect the actual financial position of the Funds on 1 April, 1939, not being based on the appropriations alone.

Again, I wish to thank the Publication Committee and the authors for their cooperation.

General Fund	
Income: Sales	$ 408.74
Contributions	10.00
Expenditures	2,107.62
Balance	$4,278.11
Lake Fund	
Income	$1,458.55
Expenditures	2,006.59
Balance (overdraft)	135.58
Hatch Fund	
Balance	$ 500.00

Respectfully submitted,
CHARLES H. BLAKE, *Chairman*
May 10, 1939.

REPORT OF THE HOUSE COMMITTEE

During the year ending March 31, 1939, the House Committee had at its disposal funds amounting to $2,155.23, made up as follows:

Balance from previous year	$ 115.23
Appropriation for 1938–1939	1,800.00
Received for use of rooms	240.00
Total	$2,155.23

The expenditures amounted to $2,400.16, the deficit being made up by special contributions. Of this amount the sum of $2,134.66 has been spent for the routine expenses, janitor, light, heat, telephone, power, etc. and $265.50 has been spent for upkeep and equipment.

Meetings have been held as follows:

The Academy	8
American Association of University Women, Boston Branch	1
American Chemical Society, Northeastern Section	6
Boston Surgical Society	3
Bureau of University Travel	1
Friends of China, Inc.	3
Geological Society of Boston	2
Japan Society of Boston	3
Mediaeval Academy of America	1
Mount Holyoke Club of Boston	1
Near East College Association	1
New England Botanical Club	9
Women's Travel Club	2
	41

A detailed list of expenditures follows:

Janitor	$ 970.00
Electricity: Light	184.34
Power	51.22
Fuel	604.58
Elevator	72.60
Gas	49.40
Telephone	103.17
Water	69.92
Ash tickets	9.90
Upkeep	260.02
Furnishing and equipment	5.50
Janitor's supplies and sundries	19.51
Total	$2,400.16

Respectfully submitted,
J. C. HUNSAKER, *Chairman*
May 10, 1939.

On the recommendation of the Rumford Committee, the Academy voted to award the Rumford Premium to Professor George Russell Harrison, of the Massachusetts Institute of Technology, in recognition of his notable work in spectrum photometry and spectrum analysis.

On the recommendation of the Treasurer, the Academy voted that the annual assessment for resident Fellows for the ensuing year be ten dollars.

The annual election resulted in the choice of the following officers and committees:

HARLOW SHAPLEY, *President*

JAMES FLACK NORRIS, *Vice-President for Class I*

WALTER BRADFORD CANNON, *Vice-President for Class II*

GEORGE GRAFTON WILSON, *Vice-President for Class III*

Arthur Stanley Pease, *Vice-President for Class IV*
Leigh Hoadley, *Corresponding Secretary*
Hudson Hoagland, *Recording Secretary*
Horace Sayford Ford, *Treasurer*
Hervey Woodburn Shimer, *Librarian*
Charles Henry Blake, *Editor*

Councillors for Four Years:

Edward L. Moreland, of Class I
Ivan M. Johnston, of Class II
Howard L. Bevis, of Class III
S. Foster Damon, of Class IV

Finance Committee:

Thomas Barbour
Ralph E. Freeman
Paul J. Sachs
Alfred L. Ripley

Rumford Committee:

Norton A. Kent, *Chairman*
Percy W. Bridgman
Harry M. Goodwin
Charles L. Norton
Harlow Shapley
George W. Pierce
George R. Harrison

C. M. Warren Committee:

James F. Norris, *Chairman*
Gregory P. Baxter
Walter L. Jennings
Tenney L. Davis
Frederick G. Keyes
Reid Hunt
Charles A. Kraus

Committee of Publication:

Charles H. Blake, *Chairman*
Edwin C. Kemble, of Class I
Ralph H. Wetmore, of Class II
Joseph H. Beale, of Class III
Robert P. Blake, of Class IV

Committee on the Library:

Hervey W. Shimer, *Chairman*
Raymond C. Archibald, of Class I
Thomas Barbour, of Class II
Nathan Isaacs, of Class III
Henry B. Washburn, of Class IV

Auditing Committee:

George R. Agassiz
Alexander Forbes

House Committee:

Abbott P. Usher, *Chairman*
William H. Lawrence
Robert P. Bigelow
Walter E. Clark

Committee on Biographical Notices:
Three Years:

Joseph H. Beale
Alfred C. Lane

Committee on Policy and Resources:

For Five Years: George R. Agassiz
For Four Years: Robert G. Dodge
For Three Years: Henry S. Dennison
For Two Years: Dugald C. Jackson, *Chairman*
For One Year: Tenney L. Davis

Committee on Meetings:

The President

The Recording Secretary

Dugald C. Jackson
Tenney L. Davis
Abbott P. Usher
Samuel H. Cross

The Corresponding Secretary announced that the following had been elected members of the Academy:

FELLOWS

Class I

Section 1. Bart Jan Bok, Lexington
Section 2. Lyman James Briggs, Washington, D. C.
Harry Edward Farnsworth, Providence, R. I.
Section 3. Clifford Burrough Purves, Cambridge
Frank Clifford Whitmore, State College, Pa.
Section 4. C. Richard Soderberg, Weston

Class II

Section 3. Gregory Pincus, Worcester
Arturo Rosenblueth, Watertown
Section 4. Frederick Fuller Russell, Brookline
William Thomas Salter, Milton

Class III

Section 1. Eugene Allen Gilmore, Iowa City, Ia.
Herbert Funk Goodrich, Philadelphia, Pa.

Section 1. John Loomer Hall, Boston
Augustus Noble Hand, New York, N. Y.
Albert James Harno, Urbana, Ill.
Robert Porter Patterson, New York, N. Y.
Thomas Walter Swan, New York, N. Y.
Section 3. Gottfried Haberler, Cambridge
Alvin Harvey Hansen, Belmont
Section 4. Chester Irving Barnard, Newark, N. J.
Ralph Edward Flanders, Springfield, Vt.
Henry Ingraham Harriman, Newton
Morris Evans Leeds, Philadelphia, Pa.
Owen D. Young, New York, N. Y.

CLASS IV

Section 2. Clarence Crane Brinton, Cambridge
Lawrence Bradford Packard, Amherst
Henry Rouse Viets, Dedham
Section 3. Henry Carrington Lancaster, Baltimore, Md.
John Matthews Manly, Chicago, Ill.
John Strong Perry Tatlock, Berkeley, Cal.
William Hoyt Worrell, Ann Arbor, Mich.
Section 4. Francis Henry Taylor, Worcester
Karl Ephraim Weston, Williamstown

FOREIGN HONORARY MEMBERS

CLASS I

Section 1. Arnaud Denjoy, Paris

CLASS II

Section 4. Sir Aldo Castellani, London and Rome

CLASS III

Section 1. Rt. Hon. Lord Atkin, London
Rt. Hon. Sir Wilfrid Arthur Greene, London
Sir William Searle Holdsworth, Oxford
Section 3. Henry Clay, Kenley, Surrey
Section 4. B. Seebohm Rowntree, North Dean, Bucks

The Academy was then addressed by Professor August Krogh, Head of the Department of Animal Physiology at the University of Copenhagen, and a Foreign Honorary Member of the Academy.

The following papers were read by title: "Serphidae in Baltic Amber, with the Description of a New Living Genus," by C. T. Brues: "Fossil Parasitic Hymenoptera of the Family Calliceratidae in Baltic Amber," by C. T. Brues.

The meeting was dissolved at 9.30 P. M.

One Thousand Two Hundred and Fifty Sixth Meeting

OCTOBER 11, 1939—STATED MEETING

The Academy met at its House at 8.16 P. M.

The President in the Chair.

There were present fifty-seven Fellows and fifteen guests.

The records of the meeting of May 10 were read and approved.

The Corresponding Secretary reported the receipt of letters accepting Fellowship from Chester Irving Barnard, Bart Jan Bok, Lyman James Briggs, Crane Brinton, Harry Edward Farnsworth, Ralph Edward Flanders, Herbert Funk Goodrich, Gottfried Haberler, John Loomer Hall, Augustus Noble Hand, Albert James Harno, Henry Ingraham Harriman, Henry Carrington Lancaster, Morris Evans Leeds, Robert Porter Patterson, Gregory Pincus, Clifford Burrough Purves, Arturo Rosenblueth, Frederick Fuller Russell, William Thomas Salter, C. Richard Soderberg, Thomas Walter Swan, John Strong Perry Tatlock, Francis Henry Taylor, Henry Rouse Viets, Karl Ephraim Weston, Frank Clifford Whitmore, William Hoyt Worrell, and Owen D. Young; and of letters accepting Foreign Honorary Membership from the Rt. Hon. Lord Atkin, Sir Aldo Castellani, Henry Clay, Arnaud Denjoy, the Rt. Hon. Sir Wilfrid Arthur Greene, B. Seebohm Rowntree, and John C. H. Wu, who was elected in 1938.

He then read an excerpt from the will of the late Arthur E. Kennelly as follows:

"*First:* I give and bequeath to the President and Fellows of Harvard College such books out of my scientific library, containing now about four thousand volumes, each volume having my book plate inserted in it, as the Librarian of Harvard College may select; to the Massachusetts Institute of Technology from the balance remaining after the selection so made by said Librarian of Harvard College such books as may be selected by the Librarian of the Massachusetts Institute of Technology; to the American Academy of Arts and Sciences, from the balance remaining after the selection made on behalf of Harvard College and the Massachusetts Institute of Technology, such books as may be selected by the Librarian of the American Academy of Arts and Sciences."

He also reported the additional bequest to the Academy of a trust fund of $1,000.

The Corresponding Secretary reported that the Council had voted the following grants from the Permanent Science Fund:

1. To Professor Orlin Biddulph, of the Department of Botany, State College of Washington, toward the cost of further studies with radioactive phosphorus in plants, $200.

2. To Professor Hyman Y. Chase, Department of Zoology, Howard University, toward the cost of further studies on the effect of ultraviolet upon cell division in marine eggs, $300.

3. To Mr. William G. Clark, Instructor, Department of Zoology, University of Minnesota, for assistance, animals and expendable materials in his investigation of the relations between adrenal cortex and membrane functions, $400.

4. To Dr. Rudolf Hoeber, Visiting Professor of Physiology, University of Pennsylvania Medical School, for compensation of an assistant in a study of the relation between molecular configuration of dyestuffs and their secretion by the kidney, $600.

5. To Mr. Lewis H. Kleinholz, Instructor in Biology, Cambridge School of Liberal Arts, for purchase of test animals in a determination of the distribution of the pituitary hormone, intermedin, $75.

6. To Professor Robert H. Lowie, Department of Anthropology, University of California, toward the expense of an investigation by Snr. Curt Nimuendaju of the Kayapo Indians and their cogeners in the region west of the Araguaya River, Brazil, $500.

7. To Mr. William G. Lynn, Associate in Zoology, The Johns Hopkins University, for the cost of illustrations of a monograph on amphibians of Jamaica, B. W. I., which has been accepted for publication, $170.

8. To Professor Thomas L. Patterson, Department of Physiology, Wayne University College of Medicine, for purchase of animals for his study of the effect of changed emotional states on body activity, $60.

9. To Professor William B. Redmond, Department of Biology, Emory University, for the purchase of animals required in a further study of a new method of immunization against malaria, $350.

10. To Mr. Edward J. Schremp, Instructor in Physics, Washington University, toward the cost of materials and equipment to be used in the determination of directional distribution of cosmic rays at St. Louis, $500.

11. To Professor C. Richard Soderberg, Massachusetts Institute of Technology, toward the cost of his investigation of the plastic properties of polycrystalline metals, the award to be contingent upon the securing by the applicant of sufficient funds to assure the continuation of this project for at least one year, $500.

12. To Mr. David M. Steven, Henry Fellow, Harvard University, toward the cost of his investigation of night blindness as an index of vitamin A deficiency, among the population of Labrador and North Newfoundland, $400.

13. To Mr. Martin D. Whitaker, Instructor in Physics, New York University, for one year's rental of a radium-beryllium source of neutrons for his studies on differential effects in slow neutron scattering, $850.

The President announced the death of eight Fellows: Harvey Cushing (Class II, Section 4), Charles Hall Grandgent (Class IV, Section 3), Joseph Grinnell (Class II, Section 3), Arthur Edwin Kennelly (Class I, Section 4), Charles Ladd Norton (Class I, Section 2), Philip Stanley Parker (Class III, Section 1), William James Mayo (Class II, Section 4), and Arthur Edward Wells (Class I, Section 4).

The President spoke briefly in regard to the policy of the Academy.

Professor Norton A. Kent, Chairman of the Rumford Committee, then presented the Rumford medals to Professor George Russell Harrison in recognition of his notable work in spectrum photometry and spectrum analysis.

The following communication was presented:

Mr. George R. Harrison: "New Methods in Spectroscopy."

One paper was read by title: "The Measurement of Hydrostatic Pressure to 30,000 kg/cm^2," by P. W. Bridgman.

The meeting was dissolved at 9.32 P. M.

One Thousand Two Hundred and Fifty Seventh Meeting

NOVEMBER 8, 1939—STATED MEETING

The Academy met at its House at 8.28 P. M.

The President in the Chair.

This meeting having been designated as Ladies' Night, there were present about 275 Fellows and guests.

The records of the meeting of October 11 were read and approved.

The Corresponding Secretary reported the receipt of a letter from Sir William Searle Holdsworth accepting his election as a Foreign Honorary Member.

A letter from Dr. Karl T. Compton, Chairman of the Committee on Awards of the National Association of Manufacturers, was read in part as follows:

"The National Association of Manufacturers has developed a Modern Pioneer Program which will commemorate the 150th anniversary of the founding of the American patent system and honor deserving inventors and research workers."

"Manufacturers throughout the nation have been invited to nominate inventors and research workers for awards. As Chairman of the Committee on Awards which will select those who are to be honored, I am inviting you and your society to submit nominees."

The Fellows were told to apply to Dr. Compton for recommendation blanks.

The President called attention to the afternoon symposium on the Internal Structure of the Earth which will be held on the day of the December meeting of the Academy at its House, to be followed by the regular evening meeting of the Academy, with a communication by Professor Reginald A. Daly.

The President then described the exhibits on view this evening after the communication, consisting of letters to the Academy from the seven Presidents of the United States who have been Fellows, beginning with George Washington; and a selection of portable sundials from the Harold C. Ernst collection now permanently on display at the Harvard College Observatory.

The following communication was presented:

Dr. George H. Edgell: "Selected Masterpieces in the Boston Museum of Fine Arts," illustrated with lantern slides.

The meeting was dissolved at 9.35 P. M.

One Thousand Two Hundred and Fifty Eighth Meeting

DECEMBER 13, 1939—STATED MEETING

The Academy met at its House at 8.15 P. M.

The President in the Chair.

There were present forty-nine Fellows and twenty guests.

The records of the meeting of November 8 were read and approved.

The Corresponding Secretary reported the receipt of letters declining election as Fellows from Eugene Allen Gilmore, John Matthews Manly, and Lawrence Bradford Packard; also a letter from Charles Collens resigning Fellowship.

The President announced the death of five Fellows: Henry Clinton Fall (Class II, Section 3), Frank Johnson Goodnow (Class III, Section 4), Waldemar Lindgren (Class II, Section 1), Floyd Karker Richtmyer (Class I, Section 2), and Frederick Adams Woods (Class II, Section 3).

The President described the exhibits to be seen in the Reading Rooms after the meeting, consisting of some unusual meteorites, seismograms illustrating earthquakes, quarry blasts, and other types of earth disturbances, and a few letters from Foreign Honorary Members of the Academy.

He outlined the Latin American program for the January meeting and spoke of its appropriateness for broadcasting. He also announced that the speaker at the April meeting would be Dr. Hu Shih, Chinese Ambassador to the United States.

The President then gave a summary of the symposium on the Internal Structure of the Earth, which had been held at the Academy in the afternoon.

The following communication was presented:

Dr. Reginald H. Daly: "New Light on the Earth's Interior: The Physical Basis of Mountain Making. Volcanic Action, and Changes of Level," with lantern illustrations.

Dr. Philip Hofer, of the Harvard College Library, then described three rare books belonging to that library, which were to be displayed after the meeting. These were as follows:

1. The Bible, in Greek, Latin, Hebrew and Chaldaean. (Also called "The Complutensian Polyglot Bible.") Alcalá de Henares (Spain) 1517–22.
2. A Collection of Elizabethan (English) Proclamations formed by Humphrey Dyson. (London), c. 1618.
3. Pushkin—"Volga" (a Fairy Tale). St. Petersburg, 1904. Presentation copy to the Tsarevitch Alexis.

The meeting was dissolved at 10.07 P. M.

One Thousand Two Hundred and Fifty Ninth Meeting

JANUARY 10, 1940—STATED MEETING

The Academy met at its House at 8.20 P. M.

The President in the Chair.

There were present fifty-three Fellows and five guests.

The records of the meeting of December 13 were read and approved.

The Corresponding Secretary reported the receipt of a letter from the Department of State announcing that the Pan-American Union will hold its 8th Scientific Congress in Washington on May 10–18, 1940.

The President announced the death of Charles Barrois, Foreign Honorary Member in Class II, Section 1, and of James Pyle Wickersham Crawford, Fellow in Class IV, Section 3.

He also mentioned that Dr. C. C. Little would speak on cancer research at the May meeting, and that the March program would probably be a social science symposium.

The President discussed the problems of the Academy library, which is not much used, despite its value as a reference library, comparing its problems to those of the American Philosophical Society library.

The following communications were presented:

Clarence H. Haring: "Liberty and Despotism in South America."

Jeremiah D. M. Ford: "Hispano-American Culture."

Dr. Frank M. Carpenter then described the collection of fossil insects on exhibition in the Reading Room.

The following paper was read by title: "Neurohumors as Chromatophore Activators," by G. H. Parker.

The meeting was dissolved at 9.53 P. M.

One Thousand Two Hundred and Sixtieth Meeting

FEBRUARY 14, 1940—STATED MEETING

Owing to a blizzard, the meeting was not attended by the required quorum of twenty-five Fellows. Since there were present seventeen Fellows and eight guests who had braved the weather, the President formally adjourned the meeting, but said that the scheduled communication would be presented.

Dr. Gregory Pincus then read a paper entitled: "Artificial Parthenogenesis and Sexual Reproduction in Animals," illustrated with lantern slides.

One Thousand Two Hundred and Sixty First Meeting

MARCH 13, 1940—STATED MEETING

The Academy met at its House at 8.20 P. M.

The President in the Chair.

There were present thirty-one Fellows and five guests.

In the absence of the Recording Secretary, Professor Tenney L. Davis was asked to assume his duties.

The records of the meetings of January 10 and February 14 were read and approved.

It was reported that letters resigning Fellowship had been received from Charles Palache and Frederick S. Woods, and one declining Fellowship from Alvin H. Hansen; that Professor George G. Wilson had resigned as Vice-President of Class III, and that the Council had appointed Professor Edmund M. Morgan to fill out his term.

It was announced that the Council had made the following grants from the Permanent Science Fund:

1. To Professor Kenneth D. Roeder, Department of Biology, Tufts College, toward the cost of an investigation in electro-physiology of sensory mechanisms in Arthropoda, $400.
2. To Professor Charles J. Lyon, Department of Botany, Dartmouth College, for the preparation of a tree-ring calendar in New England, $200.
3. To Dr. F. B. Mallory and Dr. F. Parker, Jr., Boston City Hospital, for continuing a study of chronic lead poisoning and liver pathologies, $510.
4. To Professor Neal A. Weber, Department of Biology, University of North Dakota, toward the cost of ecological studies of the ant fauna of Ethiopian and Neotropical regions, $200.

5. To Professor Alice H. Farnsworth, Department of Astronomy, Mount Holyoke College, toward the expenses, including transportation of equipment, for spectroscopic studies in astronomy in the southern hemisphere, $400.

6. To Professor Frank R. Kille, Department of Zoology, Swarthmore College, for histological studies of a seasonal cycle of the gonad in Thyone briareus, $300.

7. To Professor Alexis L. Romanoff, Department of Poultry Husbandry, Cornell University, for studies on embryo respiration, to be conducted at Harvard University, $150.

8. To Betty Holmes Huscher, Assistant Curator of Archaeology, and Harold A. Huscher, Field Assistant, of the Colorado Museum of Natural History, for archeological studies in western Colorado, $500.

9. To Professor Ernest E. Tyzzer, Harvard Medical School, to continue a study on dermatitis of human skin caused by non-human schistosome cercariae in Boston, $400.

The President announced the death of three Fellows: Herbert Vincent Neal (Class II, Section 3), Arthur Edwin Norton (Class I, Section 4) and Franklin Bache Stephenson (Class IV, Section 3).

He also appointed the Nominating Committee as follows:

Edwin B. Wilson, of Class I
Leigh Hoadley, of Class II, *Chairman*
Henry S. Dennison, of Class III
Robert H. Pfeiffer, of Class IV

The following appropriations were voted for the fiscal year ending March 31, 1941:

From the income of the General Fund, $7,200, to be used as follows:

General and Meeting expenses	$ 900
Library expenses	2,100
Books, Periodicals, and Binding	1,200
House expenses	2,000
Treasurer's expenses	900
President's expenses	100
	$7,200

From the income of the Publication Funds, $2,123.70, to be used for publication.

From the income of the Rumford Fund, $3,500, to be used at the discretion of the Committee.

From the income of the C. M. Warren Fund, $873.32, to be used at the discretion of the Committee.

It was *Voted*, to offer for consideration at the next meeting of the Academy, the following proposed amendments to the Statutes, recommended by the Treasurer and approved by the Council:

Chapter VII, Article 1, par. 1, to read: "The Treasurer shall collect all money due or payable to the Academy and all gifts or bequests made to it. He shall pay all bills due and payable by the Academy when approved by the proper officers. He shall sign all leases of real estate, in the name of the Academy. He shall be the official custodian of all bonds, stocks and other securities and, with the written approval of any one member of the Committee on Finance, he shall have full authority to sell and transfer, invest and reinvest from time to time in such manner and upon such terms as shall to him seem best, the whole or any part of the personal property of the said Academy."

Chapter XI, Article 2, par. (1), to read: "Committee on Finance, to consist of four Fellows who shall have general oversight of the funds and investments of the Academy."

The following communication was then presented:

A. E. Staley: "World Economy in Transition."

Professor Tenney L. Davis then described the historical seal of the Academy, illustrated with a lantern slide.

Dr. Donald H. Menzel explained briefly the technique of the production of "invisible" glass, some examples of which glass were on exhibition in the Library office.

Two papers were read by title: "A Revision of the Nearctic Hemerobiidae, Sisyridae, Berothidae, Polystoechotidae, and Dilaridae," by F. M. Carpenter; "Fossil Parasitic Hymenoptera of the Family Scelionidae from Baltic Amber," by C. T. Brues.

The meeting was dissolved at 10.30 P. M.

One Thousand Two Hundred and Sixty Second Meeting

APRIL 10, 1940—STATED MEETING

The Academy met at its House at 8.22 P. M.

The President in the Chair.

There were present about 200 Fellows and guests, this having been designated as Ladies' Night.

The reading of the records of the meeting of March 13 was postponed until the May meeting.

The Corresponding Secretary read a letter from the Secretary of State containing invitations to the sessions of the Pan-American Scientific Congress to be held in Washington, D. C.

The following communication was presented:

His Excellency, Dr. Hu Shih: "Some Philosophical Rebels of Seventeenth Century China."

Dr. Edward Wigglesworth then described the exhibit of synthetic gems on display in the Library office, with the methods in use for identifying them by means of "Diamondscopes."

The meeting was dissolved at 9.30 P. M.

One Thousand Two Hundred and Sixty Third Meeting

MAY 8, 1940—ANNUAL MEETING

The Academy met at its House at 8.20 P. M.

The President in the Chair.

There were present fifty-one Fellows and nine guests.

The records of the meetings of March 13 and April 10 were read and approved.

The Corresponding Secretary announced the appointment by the Council of these two committees for the ensuing year:

Amory Fund Committee: Roger I. Lee, *Chairman;* Walter B. Cannon, David Cheever, Leigh Hoadley, William C. Quinby, Edward E. Tyzzer, Soma Weiss.

Permanent Science Fund Committee: John W. M. Bunker, *Chairman;* George R. Agassiz, Kenneth T. Bainbridge, Gregory P. Baxter, Charles T. Brues, Hudson Hoagland, Walter S. Hunter, S. Burt Wolbach.

The following communication was presented:

Clarence Cook Little: "Cancer Research and the National Health Problem."

The communication was discussed at some length by a number of Fellows.

The President announced the deaths of four Foreign Honorary Members: Waldemar Christofer Brøgger (Class II, Section 1), Wilhelm Dörpfeld (Class IV, Section 2), Herbert Albert Laurens Fisher (Class IV, Section 2), and Henri Pirenne (Class IV, Section 2).

A vote of thanks was passed to WRUL for broadcasting some of the Academy meetings during the year.

The President announced a gift of $2,000 from Mrs. George R. Agassiz, the income of which is to be used to provide refreshments at the "open house" meetings of the Academy.

He also announced a gift of $2,500 from an anonymous donor, this sum to be used for an investigation of the functions of the Academy under the direction of the Committee on Policy and Resources.

Also an additional gift of $85,000 to the Permanent Science Fund held in trust by the Boston Safe Deposit and Trust Company, the annual income from which is paid to the Academy to be used "for such scientific purposes as it shall from time to time select."

The following report of the Council was presented:

REPORT OF THE COUNCIL

Since the last report of the Council there have been reported the deaths of seventeen Fellows: James Pyle Wickersham Crawford, Harvey Cushing, Henry Clinton Fall, Frank Johnson Goodnow, Charles Hall Grandgent, Joseph Grinnell, Arthur Edwin Kennelly, Waldemar Lindgren, William James Mayo, Herbert Vincent Neal, Arthur Edwin Norton, Charles Ladd Norton, Philip Stanley Parker, Floyd Karker Richtmyer, Franklin Bache Stephenson, Arthur Edwin Wells, Frederick Adams Woods; and five Foreign Honorary Members: Charles Barrois, Waldemar Christofer Brøgger, Wilhelm Dörpfeld, Herbert Albert Laurens Fisher, Henri Pirenne.

Thirty-three Fellows and seven Foreign Honorary Members were elected by the Council and announced to the Academy in May 1939.

The roll now includes 776 Fellows and 125 Foreign Honorary Members (not including those elected in May 1940).

The annual report of the Treasurer was read, of which the following is an abstract:

TREASURER'S REPORT

OPERATING RECEIPTS

Income from Investments (Schedules D and G)	$12,435.53
Income from Trustees Permanent Science Fund	8,583.00
Assessments and Admissions	4,175.00
Estate of Arthur E. Kennelly, Bequest	1,024.17
Sale of Publications	216.33
Contributions to Publication Account	10.00
Lake Publication Fund Subscriptions	678.67
Appropriation, Current Expense Fund	55.83
Total	$27,178.53

Operating Expenditures

Academy, General:		
Library, Salaries	$2,060.00	
Books and Binding	993.39	
		$ 3,053.39
General Expenses (Net)		1,126.00
House Expenses (Net)		2,130.27
President's Office		111.61
Treasurer's Office		870.96
Total		$ 7,292.23
Amory Fund:		
Publication		75.00
Publication Committee:		
General Publications	$1,449.06	
Lake Publications	749.33	
		2,198.39
Rumford Fund:		
Grants	$2,940.00	
Medals (Net)	325.10	
Miscellaneous	24.00	
		3,289.10
Warren Fund:		
Grants		1,280.00
Permanent Science Fund:		
Grants	$8,305.00	
Expenses	63.70	
		8,368.70
Total (Schedule F)		$22,503.42
(*a*) *Income Transferred to Principal*		
Appleton Fund	$ 50.67	
Centennial Fund	84.63	
Rumford Fund	151.50	
Warren Fund	48.75	
		335.55
Total		$22,838.97
Excess Receipts		4,339.56
Total		$27,178.53

(*a*) 5 per cent of estimated income for 1939–40.

DESCRIPTION OF FUNDS

General Funds

Present Balances: $50,087.09 General Fund; $2,400.00 Life Membership Fund; $3,730.91 Current Expense Fund.

Established by various subscriptions and contributions. The income of the first two funds is available for the general purposes and maintenance of the Academy—and both principal and income of the Current Expense Fund are available if needed.

Francis Amory Fund

Bequest, 1912. Present balance, $53,470.38. For the purpose of establishing a Septennial Prize and a gold medal to encourage the invention and discovery of measures for the relief of maladies peculiar to the bladder and the various organs connected with it. The bequest directed that public notice should be given of the nature and design of the Fund and contributions should be solicited in aid of it—also, that no award of the income be made until twenty-one years after the date of Mr. Amory's death (*i. e.* 1933).

Appleton Fund

Present balance, $17,458.39. Established in 1854. The Trustees under the will of Samuel Appleton turned over to the Academy, certain manufacturing stocks, of the par value of $10,000, for the purpose of constituting "a fund, the income of which is to be applied to the publication of the transaction of the said Society."

Centennial Publication Fund

Present balance, $25,678.40. Established in 1880 by gift of $1,000 from Dr. B. E. Cotting, a Fellow. Balance from subscriptions solicited by the Centennial Committee. Income is applied to publishing the transactions of the Academy.

Arthur E. Kennelly Fund

Bequest, 1939, $1,024.17. Unrestricted as to principal and income.

Permanent Science Fund

Present balance, approximately $200,000.* Fund established in September, 1928, by agreement and declaration of trust of the Boston Safe Deposit and Trust Company, acting as Trustee. Principal of Fund is held and invested by the Trustee and the annual income (approximately $6,000) used for grants for scientific research on recommendation of the Committee on the Permanent Science Fund of the Academy.

Rumford Fund

Gift of Count Rumford, 1797, $5,000 in three per cent stock of the United States. Present principal $94,968.73. Income to be applied every second year as a premium "to the author of the most important discovery or useful improvement which shall be made or published in writing during the preceding two years on heat and light."

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* Increased in April, 1940, by receipt of $85,000.

In 1832, the Supreme Judicial Court of Massachusetts decreed that the balance of income might be used for the purchase of books, papers, philosophical apparatus, making publications or procuring lecturers, experiments and investigations, thereby carrying out the general intent and purposes of Count Rumford. And, because the investment of the Fund could no longer be carried in stock of the United States, investment was permitted in "either notes or debts of the United States, or of the Commonwealth of Massachusetts or of the City of Boston, or in the stock of any bank in this Commonwealth or in notes or bonds secured by pledge of any of said stock or by mortgage of real estate in this Commonwealth or may be deposited in trust, and on interest, with the Massachusetts Hospital Life Insurance Company." This limitation is still in effect.

This decree also empowered the Academy to award the Rumford premium at any annual meeting, instead of biennially.

C. M. Warren Fund

Bequest of Cyrus M. Warren, 1891. Present balance, $16,824.64. The principal is to be held at interest and the income is to be applied toward the encouragement and advancement of research and of science in the field of Chemistry.

The following reports were also presented:

REPORT OF THE LIBRARY COMMITTEE

During the year 110 volumes and eight unbound numbers of serials were borrowed by thirteen Fellows and twenty libraries, and many more have been consulted at the Academy.

The number of volumes on the shelves at the time of the last report was 46,039. During the year 302 volumes were added, making the number now 46,341. Of this number 260 were received by gift or exchange, and 42 were purchased.

The appropriation for the year ending March 31, 1940, was $3,300, and the expenditures were as follows:

Salaries	$2,060.00
Purchase of Books and Periodicals	446.94
Binding	546.45
	$3,053.39

The European war has naturally interfered to a certain extent with the receipt of serial publications from the foreign institutions with which the Academy has exchange relations, and this accounts partly for the fewer volumes added this year. It is also due in part to the fact that a number of volumes which were at the binder's were returned too late to be included in this year's report. Volumes of journals and other serials are not counted by us as "volumes added to the library" until they have been bound and placed on the library shelves.

Respectfully submitted,
H. W. SHIMER, *Librarian*

May 8, 1940.

REPORT OF THE RUMFORD COMMITTEE

A meeting of the Rumford Committee was held October 2, 1939. At that meeting, the following grants were made:

October 2, '39

No. 348	To Professor R. W. Wood for the construction of various prisms and optical flats.	$300
No. 349	To Professor Newell S. Gingrich for the purchase of an X-ray spectrometer for use in the study of the diffration of X-rays by fluids.	375
No. 350	To Dr. E. J. Schremp for apparatus to be used in the study of the fine structure of cosmic rays, conditioned on his being able to use this sum instead of the $500 for which he asked.	400
No. 351	To Dr. H. M. O'Bryan for assistance in the study of the absorption of films of alkali metals in the far ultra-violet and the absorption of crystals above 1100 A.	400

Grants made by correspondence between October 16, '39 and March 22, '40 were as follows:

October 16, '39

No. 352	To Professor George R. Harrison for the purchase of pure metals in connection with his spectrum work.	$400

January 16, '40 No. 353	To Professor P. W. Bridgman in support of measurements of various thermo-dynamic properties of matter at high pressure.	$400
January 23, '40 No. 354	To Dr. Wilson M. Powell in support of his search for narrow showers, consisting of mesotrons, in cosmic ray phenomena.	165
March 22, '40 No. 355	To Dr. Chauncey Starr to aid in his research on the magnetic properties of various compounds and alloys.	400

Letters were sent to fifteen recipients of grants made between December 11, 1935 and January 19, 1939. Replies were received from all grantees and considerable progress was reported.

On October 11, 1939, the Rumford Medals were presented to Professor George Russell Harrison for his "Improvements in Spectroscopic Technique." Following the award of these medals, Dr. Harrison addressed the Academy on "New Methods in Spectroscopy," the first part of his address being put "on the air" by station WRUL. The latter part, being more technical, was delivered to the Academy alone. As a matter of record it may be stated that this was the first time that a meeting of the Academy was broadcast.

Respectfully submitted,

Norton Adams Kent, *Chairman*

May 8, 1940.

Report of the C. M. Warren Committee

The Committee had at its disposal during the fiscal year 1939–1940, $1,280.

Grants were made to aid scientific investigation totalling this sum.

Since the last annual report, grants have been made as follows:

Dr. I. Amdur, Massachusetts Institute of Technology, $500, to be used for apparatus necessary in his experimental determination of the potential fields between atoms and molecules.

Professor Robert C. Elderfield, Columbia University, $200, to be used in the study of toxic substances in loco weed.

Professor J. W. McBain, Stanford University, $180, for the purchase of additional X-ray apparatus to be used in the investigation of the crystal structure of the various constituents of soap colloids.

Professor Gerhard Dietrichson, Massachusetts Institute of Technology, $300, for the purchase of apparatus needed in his determination of gas densities.

Professor J. Leslie Jones, Howard University, $300, to be used in the study of kinetics of gas reactions. Money to be used for apparatus.

Reports of progress have been received from: Messrs. Dietrichson, Heidt, Huntress, Johnson, Jones, McBain, and Schmidt.

During the year, the papers listed below, which have not been previously reported, describe investigations aided by the Warren Fund.

Lawrence J. Heidt. Quantum Yields and Kinetics of a Photo-sensitized Production of Reducing Sugars from Sucrose in Aqueous Solutions of Uranyl Sulfate by Visible and Ultraviolet Light. J. Am. Chem. Soc., *61*, 3223 (1939).

Ernest H. Huntress and Frederick H. Carten. I. Chlorosulfonic Acid as a Reagent for the Identification of Aryl Halides. J. Am. Chem. Soc., *62*, 511–514 (1940).

Margaret K. Seikel. II. Piperidyl Derivatives of Aromatic Halogenonitro Compounds. J. Am. Chem. Soc., *62*, 750–756 (1940).

Ernest H. Huntress and Frederick H. Carten. III. Chlorosulfonic Acid as a Reagent for the Characterization of Aromatic Ether. J. Am. Chem. Soc., *62*, 603–604 (1940).

J. Leslie Jones. Kinetic Studies on Iodine Derivatives. II. The Thermal Decomposition of Iodomethyl Ether. (Contribution from the Chemical Laboratory of Howard University. The final report of the present investigation will be published in one of the journals with grateful acknowledgment to the Cyrus M. Warren Fund.)

A. C. Batchelder and Carl L. A. Schmidt. The Effects of Certain Salt Mixtures on the Dissociation of Glycine and Alanine. The Journal of Physical Chemistry, *Vol. 43*, No. 9, December, 1939.

James F. Norris, *Chairman*

May 8, 1940.

REPORT OF THE COMMITTEE OF PUBLICATION

During the year 1939–1940, there have been published one number of the Memoirs and eight numbers of the Proceedings. Another Fascicle of the Monumenta Palaeographica Vetera has appeared.

It is again a pleasure to the Editor to record his appreciation of the helpfulness of the committee and the various authors. Special mention should be made of the assistance of Prof. J. R. Ware, which made possible the use of Chinese type in the articles by Davis and Chao.

Since the Treasurer's report this year will be more detailed than has been customary in the past, it does not seem necessary to repeat here the information which will be in that report. It is only proper to remark that a considerable part of the balance in the general fund is earmarked for papers just issued or going through the press.

If the retiring chairman may be permitted two comments on policy, he will suggest that part time clerical assistance would greatly facilitate the work of his office and that the series of Memoirs should be abandoned except for the continuation of one or two monographs which are still incomplete.

Respectfully submitted,
CHARLES H. BLAKE, *Chairman*

May 8, 1940.

REPORT OF THE HOUSE COMMITTEE

During the year ending March 31, 1940, the House Committee has had at its disposal funds amounting to $2,256, made up as follows:

Appropriation for 1939–1940	$2,000
Received from other societies for use of rooms	256
Total	$2,256

The expenditures amounted to $2,386.27. Of this the sum of $2,121.38 was spent for the routine expenses, janitor, heat, light, telephone, etc. and $264.89 for upkeep, furnishings and equipment. The most important items in this latter category were $80.88 for roof repairs and $83.40 for an exhibition case.

Owing to our limited appropriation and the necessity for using our funds for such emergencies as repairs to the roof and the plumbing, we have been obliged for some years to neglect the needed repainting of the interior of the building. We hope to do some parts this summer, though it will not be possible to do much with the funds at our disposal.

Meetings have been held as follows:

The Academy	8
Archaeological Institute of America, Boston Chapter	1
Boston Surgical Society	2
Friends of China, Inc.	1
Geological Society of Boston	1
Japan Society of Boston	3
Mediaeval Academy of America	1
Mount Holyoke Club of Boston	1
New England Botanical Club	8
Total	26

The Northeastern Section of the American Chemical Society, which has held monthly meetings at the Academy from October to May for several years, found that our Lecture Hall had become too small for its purpose and is now holding its meetings elsewhere.

The Council Chamber has been used for the Academy Council and Committee meetings, and also by the Trustees of the Children's Museum, the New England Farm and Garden Association, etc.

A detailed list of expenditures follows:

Janitor	$ 980.00
Electricity: Light	201.37
Power	58.76
Fuel	576.45
Elevator	69.60
Telephone	111.25
Gas	52.40
Water	40.48
Upkeep	152.99
Furnishing and equipment	111.90
Janitor's supplies and sundries	31.07
Total	$2,386.27

Respectfully submitted,
ABBOTT P. USHER, *Chairman*

May 8, 1940.

The Corresponding Secretary announced that the following had been elected members of the Academy:

FELLOWS

CLASS I

Section 2. Frederick Vinton Hunt, Belmont
J. Robert Oppenheimer, Berkeley, Cal.
Section 3. William Lloyd Evans, Columbus, Ohio
Section 4. Harold Locke Hazen, Belmont
John Wulff, Cambridge

CLASS II

Section 2. Albert Francis Blakeslee, Cold Spring Harbor, N. Y.
Paul Christoph Mangelsdorf, College Station, Texas
Section 4. William de Berniere MacNider, Chapel Hill, N. C.
Donald Dexter Van Slyke, New York, N. Y.
Paul Dudley White, Brookline

CLASS III

Section 1. Lon Louvois Fuller, Durham, N. C.
Lloyd Kirkham Garrison, Madison, Wis.
Henry Tilton Lummus, Swampscott
Section 2. Robert Granville Caldwell, Belmont
Thomas Head Thomas, Cambridge
Section 3. Lewis Cecil Gray, Washington, D. C.
Alvin Saunders Johnson, New York, N. Y.
Section 4. Henry Bruere, New York, N. Y.
Richard Spencer Childs, New York, N. Y.

CLASS IV

Section 2. Herbert Eugene Bolton, Berkeley, Cal.
Section 3. Serge Elisséeff, Cambridge
Werner Wilhelm Jaeger, Watertown
Edgar Howard Sturtevant, New Haven, Conn.
Section 4. Archibald MacLeish, Washington, D. C.

FOREIGN HONORARY MEMBERS

CLASS IV

Section 2. Martin Persson Nilsson, Lund
Section 4. Fernand Baldensperger, Paris
Paul Hindemith, New Haven, Conn.
Igor Strawinsky, Paris

On the recommendation of the Council, it was *Voted,* to amend Chapters VII and XI of the Statutes, as follows:

CHAPTER VII—*The Treasurer and the Treasury*

Article 1, par. 1, to read as follows:

The Treasurer shall collect all money due or payable to the Academy and all gifts or bequests made to it. He shall pay all bills due and payable by the Academy when approved by the proper officers. He shall sign all leases of real estate in the name of the Academy. He shall be the official custodian of all bonds, stocks and other securities and, with the written approval of any one member of the Committee on Finance, he shall have full authority to sell and transfer, invest and reinvest from time to time in such manner and upon such terms as shall to him seem best, the whole or any part of the personal property of the said Academy.

CHAPTER XI—*Standing Committees*

Article 2, to read as follows:

At the annual meeting, the following Standing Committees shall be elected by ballot to serve for the ensuing year:

(1) Committee on Finance, to consist of four Fellows who shall have general oversight of the funds and investments of the Academy.

On the recommendation of the Treasurer, it was *Voted,* that the annual assessment for resident Fellows for the ensuing year be ten dollars.

The annual election resulted in the choice of the following officers and committees:

HARLOW SHAPLEY, *President*
PERCY W. BRIDGMAN, *Vice-President for Class I*
S. BURT WOLBACH, *Vice-President for Class II*
SIDNEY B. FAY, *Vice-President for Class III*
ARTHUR S. PEASE, *Vice-President for Class IV*
ABBOTT P. USHER, *Corresponding Secretary*
HUDSON HOAGLAND, *Recording Secretary*
HORACE S. FORD, *Treasurer*
HERVEY W. SHIMER, *Librarian*
ROBERT P. BLAKE, *Editor*

Councillors for Four Years:

ARTHUR A. BLANCHARD, of Class I
WILLIAM B. CASTLE, of Class II
HENRY P. KENDALL, of Class III
CHARLES H. TAYLOR, of Class IV

Councillor for Three Years:

Arthur N. Holcombe, of Class III

Councillor for Two Years:

Austin W. Scott, of Class III

Committee on Policy and Resources:

Five Years: Tenney L. Davis

Finance Committee:

Thomas Barbour
Ralph E. Freeman
Paul J. Sachs
Alfred L. Ripley

Rumford Committee:

Norton A. Kent, *Chairman*
Percy W. Bridgman
Harry M. Goodwin
Harlow Shapley
George W. Pierce
George R. Harrison
Robert B. Lindsay

C. M. Warren Committee:

Frederick G. Keyes, *Chairman*
Gregory P. Baxter
Walter L. Jennings
Tenney L. Davis
Reid Hunt
Charles A. Kraus
Grinnell Jones

Committee of Publication:

Robert P. Blake, *Chairman*
Edwin C. Kemble, of Class I
Ralph H. Wetmore, of Class II
Joseph H. Beale, of Class III
Robert P. Casey, of Class IV

Committee on the Library:

Hervey W. Shimer, *Chairman*
Raymond C. Archibald, of Class I
Thomas Barbour, of Class II
Nathan Isaacs, of Class III
Henry B. Washburn, of Class IV

Auditing Committee:

George R. Agassiz
Alexander Forbes

House Committee:

Ernest F. Langley, *Chairman*
William H. Lawrence
Robert P. Bigelow
Walter E. Clark

Committee on Biographical Notices:

Three Years:

Raymond C. Archibald
Samuel E. Morison

One Year:

J. Seelye Bixler, *Chairman*

Committee on Meetings:

The President
The Recording Secretary
Dugald C. Jackson
Tenney L. Davis
Abbott P. Usher
Samuel H. Cross

Insert on page 112.

Dr. Bart J. Bok explained the exhibit of astronomical photographs, mostly from South Africa, illustrating recent work on stars and galaxies.

One paper was read by title: "The Old World Species of the Celastraceous Genus *Microtropis* Wallich," by E. D. Merrill and F. L. Freeman.

The meeting was dissolved at 10.15 P. M.

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ERNEST WILLIAM BROWN (1866–1938)

Fellow in Class I, Section 1, 1912

The Academy is proud to have numbered among her fellows all three of the distinguished men who in this hemisphere long worked on the problem of the moon's motion. I refer to Simon Newcomb, admitted to the Academy in 1860, to George William Hill in 1873, and to Ernest William Brown in 1912. They all became presidents of the American Mathematical Society, and Hill and Brown were the greatest mathematical astronomers who ever achieved their careers in America. Two of them were born in the British Empire, Newcomb in Nova Scotia and Brown at Hull, England, on 29 November 1866.

Brown graduated from the University of Cambridge (A.B. 1887, A.M. 1891, Sc.D. 1897). During a year of postgraduate study there his chief advisor was Professor G. H. Darwin, who recommended him to study Hill's classic paper "Researches in the lunar theory." He thus became started on a field of research which was to engage his attention for more than 45 years.

In 1891 he came to America as an instructor in mathematics at Haverford College and continued there, with advanced academic title, until 1907, and constantly active in research. During this period there are in his bibliography forty-five titles, including *An Introductory Treatise on the Lunar Theory* (1896), and his Adams Prize Essay for 1907 on *The Inequalities in the Motion of the Moon due to the Direct Action of the Planets*. He was elected a fellow of the Royal Society (1898), was awarded the gold medal of the Royal Astronomical Society (1907) and served as joint editor of the *Transactions* of the American Mathematical Society from its foundation until 1906. In 1903 mathematicians of America ranked him as seventh among the first 80. Beginning with an extension of Hill's work Brown was gradually led to a complete development of a lunar theory that includes the gravitational action of every particle of matter which can have a sensible effect on the moon's motion. This work is summarized in the great *Memoirs* of the Royal Astronomical Society, 1897–1908.

Professor Brown was professor of mathematics at Yale University 1907–21; Sterling professor of mathematics 1921–31; the first Josiah Willard Gibbs professor 1931–32; Josiah Willard Gibbs professor Emeritus 1932 until his death at New Haven, 22 July 1938. He became naturalized as a citizen of the United States in January 1922.

The Yale authorities recognized the importance of Brown's work in the Haverford period by arranging special facilities for its continuation and undertook to provide the funds required for both the preparation and the publication of his *Tables of the Motion of the Moon* (3 vols., 1919). These tables have been uniformly used in nautical almanacs of the world since 1923, and predicted the 1923 eclipse with surprising accuracy. For an account of many other remarkable scientific achievements, activities, and honors, the reader must turn elsewhere.[1]

Professor Brown contributed also to the popularization of his subject by writing a number of articles, and many reviews of new publications. Like Newcomb, he delighted in high climbing on Swiss mountains; in early life he was an expert oarsman. Professor Schlesinger has told us that he was an authority on Gilbert and Sullivan operas, on the Bab Ballads, and on Lewis Carroll's poems, all of which he could recite from memory without hesitation. In youth he expected to be a concert pianist, and his musical settings of Haverford College songs were published. He sang in choruses and choirs, and at one time he was president of the Oratorio Society in New Haven.

He was never married.

R. C. Archibald

WILLIAM WALLACE CAMPBELL (1862–1938)

Fellow in Class I, Section 1, 1911

William Wallace Campbell, versatile astronomer and able administrator, was one of the leaders whose driving force and imagination helped to devise the new methods that have made modern astronomy such a fruitful field of research.

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[1] There is a detailed sketch with a complete bibliography and portrait in R. C. Archibald, *A Semicentennial History of the American Mathematical Society, 1888–1938* (New York, 1938). See also the sketches of Dirk Brouwer in *Science*, 7 Oct. 1938, n. s., vol. 88, p. 316–318, and of F. Schlesinger, in Amer. Math. So., *Bulletin*, vol. 45, p. 343–344.

Campbell was born on a farm in Hancock County, Ohio, in 1862. After receiving his early education in country schools, he entered the University of Michigan, graduating with the B.S. degree in 1886. Campbell spent two years as professor of mathematics at the University of Colorado, and three years as instructor in astronomy at the University of Michigan before joining the staff of the recently-founded Lick Observatory, on Mt. Hamilton, in California, in 1891.

His early work at Lick provided a clear indication of the pioneering qualities that were soon to make him a leader among astronomers of the world. The possibilities of the spectroscope as a tool for research had just begun to be exploited, and Campbell set out to make full use of this exciting instrument in connection with the 36-inch refractor. Visual studies of emission lines in the spectra of stars, nebulae, and comets laid the foundation for the more powerful photographic methods that were to come later. An important series of spectroscopic observations on the planet Mars were undertaken by Campbell in 1894, in an effort to establish the presence or absence of water vapor in the Martian atmosphere. His conclusion that water vapor, if it were present on Mars at all, must be much less plentiful than in the Earth's atmosphere has since been repeatedly verified under much more favorable observing conditions.

The first director of the Lick Observatory, Holden, had been succeeded by Keeler in 1898, and, when the latter died two years later, Campbell, in 1901, was chosen to succeed him. It was during these years that Campbell was establishing the standards of observational precision that have made the name of Lick Observatory synonymous with high-quality observations. The determination of radial velocities had been carried out by visual methods for a few stars and nebulae. With the aid of a specially designed spectrograph, donated by D. O. Mills, and attached to the 36-inch refractor, Campbell, in 1896, set out to measure the radial velocities of all the stars in the northern skies that were brighter than magnitude 5.5. In 1903 a 36-inch reflecting telescope and spectrograph were established by the Lick Observatory at Santiago, Chile, to provide for observations of the southern stars. The successful completion of this ambitious program by Campbell, J. H. Moore, and others, was signalized by the publication, in 1928, of the radial velocities of some 2700 stars, probably the most important single contribution to our knowledge of stellar motions that has ever been made. From the outset the errors of the velocity determinations were almost unbelievably small, averaging about half a kilometer per second. Such precision has not been improved on up to the present day. An interesting and at first secondary outcome of the radial velocity program was the discovery of large numbers of double stars, as evidenced by periodic velocity variations.

An instance of Campbell's versatility in research was his successful securing of observations at seven total solar eclipses, from Mexico and the United States to Australia and India. The spectrum photographs obtained on these expeditions are the basis for D. H. Menzel's fundamental contribution, published in 1932, to our knowledge of the solar atmosphere. Specially-designed equipment was employed by Campbell at the Australian eclipse of 1922 to verify definitely one of the predictions of Einstein's theory of relativity, namely, that light rays passing close by the sun are deflected by the sun's gravitational field.

On his return from the Australian eclipse he was prevailed upon to serve the University of California as president, although nominally retaining his observatory directorship in the hope that he might soon be permitted to return to his work. This hope was never realized and Campbell yielded to retirement in 1930. The illness to which he fell a victim in that year continued to plague him for eight years, and finally brought on his death on June 14, 1938.

During his long and, for astronomy, profitable career, Campbell received many honors in recognition of his service to science, including eight honorary degrees from American and foreign universities, the Lalande and Janssen medals of the Paris Academy, the Draper medal of the National Academy of Sciences of the United States, the Bruce medal of the Astronomical Society of the Pacific, and the Gold Medal of the Royal Astronomical Society of England.

LEO GOLDBERG

HARVEY CUSHING (1869–1939)

Fellow in Class II, Section 4, 1914

Vice-President for Class II, May 1919–May 1923

Harvey Cushing, surgeon, neurologist, medical investigator, bibliophile, historian and writer was born in Cleveland, Ohio, April 8, 1869, and died in New Haven, Connecticut, October 7, 1939. He was the descendant of a long line of doctor folk whose original American ancestor, Matthew Cushing, landed at Hingham, Massachusetts, in 1638. Educated at Yale College and at the Harvard Medical School, he received a thorough training in surgery under William Stewart Halsted at the Johns Hopkins Hospital in Baltimore. There his dynamic and artistic disposition received its major stimuli. There he made friends with William Osler and acquired that love of books that so greatly flavored his writings in the succeeding years. There he learned the scientific method and began his laboratory efforts, and there he acquired the precise and gentle surgical technique that was to allow him to establish the field of neurological surgery.

His consuming ambition and devotion to his profession were above that of most doctors and his restless and perfectionist attitude made him sceptical and critical of much that went on in his day. The result was an output in work and thought of extraordinary value to his profession. After a complete training in general surgery he entered the field of neurological surgery. For thirty years he tilled this field assiduously both in the clinic and in the laboratory. The 330 books, papers and monographs which he wrote deal largely with the nervous system, but the historical contributions and orations on general topics represent an unusual breadth of interest and work. And unheralded are the greater number of hours put in with the manuscripts and efforts of his pupils.

His tireless energy showed little let-down as the years passed by. A serious illness during the World War when he drove himself at top speed in forward hospitals passed by scarcely noticed and in his later years a painful malady of his peripheral vessels was borne with such stoicism that only his intimates knew of his continuous suffering.

It was only natural that such an abounding energy should produce great works. By 1913 when he gave the surgical oration at the International Congress of Surgery, he was one of the most distinguished surgeons of this country. At this time the Harvard Medical School brought him to Boston as Moseley Professor of Surgery and he settled down for his major productive years. Here as Surgeon-in-Chief of the new Peter Bent Brigham Hospital his labors established the safe limits for surgical procedures on the central nervous system. Here he wrote the two-volume life of Sir William Osler for which he received the Pulitzer Prize in Letters in 1926. Here he became the master of a school for surgeons such as only his teacher, Halsted, had achieved before him.

To many he was looked upon as a great teacher, and here indeed lay one of his greatest gifts to posterity, for no master has had a more devoted group of pupils who so obviously have followed in emulation the footsteps of their teacher. His exquisite handling of tissues, his perfect care of the patient, his leaving no stone unturned no matter what the effort, were the lodestones which drew young men to him in great numbers. His method of teaching, the apprenticeship system, was simple, and since Cushing was a man of few words it resulted in teaching through example. It has often been said that Harvey Cushing was a severe task-master. He was when it was necessary, but he certainly never exacted greater labors of his pupils than he set for himself, and it should not surprise us that such an ardent and serious person was impatient with incompetence and slovenliness. His perfectionist attitude brooked no compacts with mediocrity and throughout all his relations with pupils there was always time for wise counsel and friendly advice. The pupils always knew, even without a spoken word, that their interests lay close to his heart.

This dynamic personality has gone from our midst. He greatly enjoyed his association with the American Academy of Arts and Sciences, and we who profited from his association with us make grateful acknowledgment here for his efforts to better the comfort and the happiness of the people of his time.

Elliott C. Cutler

EDWARD MURRAY EAST (1879–1938)

Fellow in Class II, Section 2, 1911

In the months since Dr. East's death a number of excellent accounts of his life and work have appeared.* They have been written by men who knew him well, and who are capable of evaluating his contributions to science. Since these biographies contain the essential facts with regard to his life and work, it has seemed appropriate for me to confine this account to his career as a teacher. He was, in the opinion of his students, a very great one and it was in that role that I knew him best. I have a very vivid memory of my first meeting with him when I came east to begin graduate work in the spring of 1919. I knew nothing about him personally, aside from the assurance of one of my professors that he was "a very genial and generous man to work with." This was scarcely an adequate preparation for one's first sight of him. I knocked and there was a sharp, clear "come in!" Facing me across the desk was a neatly dressed middle-aged man of average size, whose strong features threw into high relief his direct, determined, impersonal stare. His light, silky hair, already beginning to thin, scarcely veiled the square lines of his skull. Then as always, he was meticulously smooth-shaven, with a large, firm, and expressive mouth. He welcomed me pleasantly and in a quick, business-like fashion arranged details of residence, instruction, and research. He was curt but considerate, and increased my confusion by treating me as an equal.

Those of us who feel that Dr. East was a very great teacher base our opinion on his results rather than on any evident feature of his technique. The training of scholars is an art and artists are recognized by their masterpieces rather than by their techniques. One can only suggest that certain characteristics which in greater or lesser degree were passed on to most of his students were important elements in their training. One of these characteristics was his disregard of all supposed authorities. A small handful of biologists he always spoke of with respect, even when their opinions differed from his. The rest, in conversation at least, were disposed of in vigorous and picturesque terms: "Don't waste time wading through so-and-so's papers; he's a useless old dodo." It was this same characteristic, I suppose, which had given him courage, as a chemist and an outsider, to plunge into corn-breeding, and to tell the experts how it should be done. It was certainly one of his outstanding traits and all of his students learned to judge scientific theories on their own merits and without reference to the eminence of their sponsors.

Another characteristic which he passed on to many of his students was a strong sense of relative error. His clear mathematical mind not only grasped the principle of significant figures in computations, it had seen through to a more basic principle, which applied to all experimentation; refined methods are to be used only when the data are worthy of them. If there are gross errors inherent in the method or in the data, their refinement gives only specious accuracy to the result. He often repeated a remark which he ascribed to one of his teachers, "It is seldom necessary to weigh a ton of hay on a Joly balance."

When the problem merited it, however, no one could be more exacting. He was pleased as a boy when he was able to find data for calculating the percentage of error in his own experiments. Plant labels have more ways of getting shuffled than even most botanists realize. Foreign seeds may contaminate the seed pan; even a well-trained gardener can mix a few plants when transplanting thousands of seedlings; the plant set out in the field may die and be replaced by a volunteer seedling from last year's crop. Over a series of years Dr. East assembled critical data on the percentage of such accidents in his pedigree cultures and calculated the probability that any particular plant was not entitled to the label which it bore.

In passing on to what seems to me was his greatest gift as a scholar or a teacher of scholars, we enter a more debatable field. Disregard of authority and significant accuracy were subjects which he discussed frequently with his students. This other trait went deeper and though he never discussed it, association with him produced a similar attitude in many of his students. This attitude, difficult to put into words, resulted from an appreciation of truth as something relative. To him no working hypothesis was ever so completely proved that it could be taken for granted. One worked not with a set of known laws and another set of unproved hypotheses but with a whole collection of hypotheses (conflicting if need be) which passed from the more likely to the less likely. He possessed the ability to think about facts independently of the hypotheses with which they are usually associated and he stimulated the development of this quality in his students. I suppose this must have been acquired (or at least enhanced) through his close association with William Bateson. It is certainly a characteristically Batesonian attitude and is but one of several fundamental resemblances between the two men.

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* Emerson, R. A. 1939. Science N. S. **89**: 51.
Jones, Donald F. 1939. Genetics **24**: 2 P. L., frontispiece.
Sax, Karl. 1939. Rec. Gen. Soc. Amer. **8**: 11–12.

Like any great teacher he treated his students as individuals. The work of some was closely supervised, others were left largely to their own devices, even when they produced no immediate results. He had in the back of his mind a definite conception of the kind of work a certain student might be doing a decade or so later. In the few cases which I know about personally, time has borne out his estimates. Several of us were very negligent in our dress and he made no more than an occasional amused comment on our lack of hats, neckties, and shoe polish. In the case of Mr. X, however, he was wise enough to see that such negligence would become a real barrier to achievement, and he criticized X repeatedly and severely for his sloppy dress.

Dr. East would have been the first to insist that the outstanding success of his students was due quite as much to the remarkable institution in which he worked as to his own individual efforts. Most of the men trained under him were students at the Bussey Institution of Harvard University, one of the most successful experiments in higher education which has yet been undertaken in this country. A few brilliant biologists, East, Castle, Wheeler, Brues, Ames, and Bailey, were associated informally with a small group of students in an antiquated building far enough removed from the rest of the University to permit the development of group individuality. There was little expensive equipment; when apparatus was needed it was constructed in so far as possible from the materials in the ancient stock room, but there were ample opportunities for growing experimental plants and animals and a rather complete freedom from institutional red tape. The Bussey rapidly became an acknowledged center for biological research and the few scholars trained there have made outstanding records. Practical considerations caused it to be discontinued three years before Dr. East's death. It was, however, a successful experiment and whenever a Bussey man is associated with graduate education he tries, consciously and unconsciously, to create the kind of an atmosphere in which he received his own training. In this way Dr. East and his colleagues continue to influence graduate education just as their research is a continuing force in Biology.

EDGAR ANDERSON

OLIVER LANARD FASSIG (1860–1936)

Fellow in Class II, Section 1, 1935

Oliver Lanard Fassig, dean of American climatologists, was born at Columbus, O., Apr. 5, 1860, son of Mathias and Elizabeth (Lanard) Fassig. He was most widely known for his comprehensive treatment of the climate and weather of Baltimore, of Maryland and Delaware, and of Puerto Rico, models for American studies of local climatology. While Robert DeCourcy Ward was interpreting European work in general climatology to America, Fassig was applying European methods to our records. Ward was the teacher interested in principles and broader generalizations, Fassig the Weather Bureau official confronted with an insistent local demand for an interpretation of his station and section records.

Dr. Fassig was much more than a local climatologist, however. Following graduation from Ohio State University, in 1882, he entered the U. S. weather service at Washington in Jan., 1883; serving there three years, except for several months at Fort Myer, for instruction the first year. In Dec., 1885 he was sent to New Haven as assistant in order to study electrical methods at Yale. In 1887 he was returned to Washington, and from the following June served as bibliographer and librarian till 1896, compiling a great bibliography of meteorology, including some 100,000 titles. He was made chairman of the section on History and Bibliography of the International Meteorological Congress, Chicago, 1893. As Secretary of the Congress, he edited the extensive proceedings. His contacts with meteorologists from abroad led him to take a year's leave of absence to study in Germany, 1896–7. He became a member of the German Meteorological Society.

After his return from Europe Fassig was made assistant at the Baltimore station of the Weather Bureau, and, while at Baltimore, studied at Johns Hopkins, winning the Ph.D. degree in meteorology there (the first in the U. S.) in 1899. His thesis was on the broad pressure relations of distinctive types of March weather over North America. In 1898 he was happily married to Anne Green McCoy, of Annapolis, Md., who survives him. From 1900 to 1905 he was in charge of the Baltimore station, and published his studies of the climate and weather of that city. He also improved observational practice by inventing a rain-time recorder and a sky camera. In 1905 Dr. Fassig was transferred to Mt. Weather to inaugurate the aerological work there, as director of upper air research. Recognition soon came from abroad: he was elected to the International Commission of Scientific Aeronautics.

In 1907 he returned to Baltimore, where he was again in charge until 1909. Dr. Fassig served not only the Weather Bureau, but also the Maryland State Weather Service, and gave instruction in meteorology and climatology at Johns Hopkins from 1896–1909. From 1909 to 1912, in charge at San Juan, P. R., he came to love the tropics, and published on the climate of the island. After 6 years more at Baltimore, 1912–1918, Fassig organized and directed the Signal Corps School of Meteorology during the war, putting about 400 men through a 1½ to 3 months intensive course in meteorology, including observing and forecasting, under three instructors, at College Station, Texas. At this time he was also secretary of the Association of American Geographers, 1918–1919. In 1919, he returned to Puerto Rico to organize the Caribbean weather and climate service of the Weather Bureau.

Now Dr. Fassig became a traveling ambassador among the numerous countries in and about the Caribbean. His pleasing, comfortable manner smoothed his mission, and in 1920 the Caribbean service began to function. Not only did he arrange for the immediate interchange of daily weather reports, especially for hurricane warnings, but also for the month by month rendition for publication of the observations from numerous non-telegraphic stations, for climatological purposes. Dr. Fassig's aerological experience at Mt. Weather could be counted on to bring about his early establishment of pilot balloon observations at San Juan, which from 1919 to 1926 were during the hurricane season only, but from 1926 were continued throughout the year. With the development of aviation, his published paper on the trade winds of the Caribbean has been much in demand. A complete presentation of these upper air observations and an interpretation of the atmospheric circulation over Puerto Rico bulk large in Fassig's comprehensive manuscript on the climate of Puerto Rico. His hurricane forecasting and devotion to duty in spite of personal peril saved hundreds of lives and won for him the great respect of the Puerto Ricans.

In 1930, when Dr. Fassig would have been retired for age in the field service, he was brought to Washington to head the Climatological Division, bringing to its leadership for the first time, a man who was heart and soul a climatologist. In the two brief years before he was retired he made his scientific ideas and enthusiasm felt throughout the service. Foreign recognition came again in his election to the International Climatological Commission, in 1932. In the four years from his retirement until his death, Dr. Fassig, as Research Associate at Harvard, concluded his work on the hundreds of tables and diagrams on the climate of Puerto Rico, spending his winters on the island. He was Visiting Professor at the School of Tropical Medicine, 1933–35, continuing a connection as lecturer on climatology there, 1926–30. He was in Washington, D. C., preparing the text on Puerto Rico, when he was injured by an automobile and died two weeks later, December 6.

Dr. Fassig was a quiet, unassuming, unhurried scientist. His interests embraced many phases of science, thus he was a fellow of the Am. Assn.

for the Adv. of Science, a member of the Am. Academy of Arts and Sciences and of the Ecological Society of America. He was a delightful companion: he always had time to tell some amusing story out of his wealth of human experience in a polar relief expedition, in a devastating hurricane in the tropics, or in the run of an active life as observer, forecaster, teacher, and administrator. Absolute fairness and sympathetic understanding characterized his dealings not only with his equals but with those under him. He had the courage to do what he thought right even at considerable personal sacrifice, as when he refused to enter politics on behalf of his chief.

A fuller account of Dr. Fassig's life and work and a portrait is to be found in the Bulletin of the American Meteorological Society, of which he was a charter member (Jan., 1937, vol. 18, pp. 28–34, including a bibliography of 78 titles).

Charles F. Brooks

HENRY FAY (1868–1939)

Fellow in Class I, Section 3, 1909

Henry Fay was born in Williamsburg, Pennsylvania, January 12, 1868. His father, Dr. John Fay, was for most of his life surgeon for the Pennsylvania Railroad. Fay's boyhood was spent in Altoona, Pennsylvania, where he attended the Altoona High School and a private school after which he entered Lafayette College, receiving the A.B. in 1889 and A.M. in 1892. Many years later he was elected a Trustee of Lafayette and was given its Honorary D.Sc. in 1915. Although Fay was never strong, he was always interested in sports, acting as manager of the football team and becoming one of the best collegiate tennis players in Pennsylvania.

Following his graduation he entered the laboratory of the Pennsylvania Railroad working part time under Dr. C. B. Dudley, chief chemist of the railroad, and one of the pioneers in the field of materials testing. It was during this period that Fay developed that interest in the field of metals which was to dominate all his later activities.

In 1895 he received the Ph.D. degree from Johns Hopkins after serving for several years as lecture assistant to Ira Remsen. In the fall of 1895 he was called to the Massachusetts Institute of Technology as Instructor advancing rapidly through the lower grades to the rank of professor in 1907.

His work in Analytical Chemistry was outstanding in its precision and attention to detail. It was said of him that he could carry out successfully the most difficult kind of analytical work in evening clothes and without a laboratory apron for protection. He was intolerant of mediocrity and students working under him were impelled to give their best. In spite of his great reserve he inspired not only the respect but deep affection of those who came to know him well. His many kindnesses to students in the way of friendly advice and often financial help are known only to those who benefited. Those of us who were closely associated with him often suspected that he had helped a boy when help was needed and occasionally we learned it from the boy himself, never from Fay.

His early interest in the application of the microscope to the study of the properties of metals is indicated in a paper published in 1898 on "The Segregation of Carbon in a Piece of Boiler Plate." At this time Metallography was virtually an unknown branch of science and Physical Metallurgy did not exist. He was one of the American pioneers in the field that is now universally recognized.

Throughout the rest of his career his activities in this important division of Metallurgy rapidly increased as the publication of some twenty important papers and a great number of minor contributions indicates. He was for seven years consulting metallurgist for the Gillette Razor Company and had much to do with the early developments in the production of razor steel. For nearly fifteen years he was metallurgist for the Watertown Arsenal and many of his most important contributions are in the form of reports to the Chief of Ordnance, most of which were published in "Tests of Metals."

During the Great War, Fay was consultant for the Winchester Repeating Arms Company and his advice was sought by and generously given to various arsenals and to industrial firms making munitions. Although he was urged repeatedly to accept an important position in the Ordnance Department, he felt that he could be of more value to his country as an independent civilian advisor. The constant physical and mental strain of these advisory duties contributed in no small degree to the beginnings of the disease from which he suffered for more than twenty years.

Dr. Fay's active and productive career ended with the close of the War but for the rest of his life he retained a vivid interest in the rapid developments in his chosen field and was a constant inspiration to those whom he was able to see at his home.

On the fly-leaf of a volume of his collected papers which had been bound for his own use is pasted a little newspaper clipping called "My Creed" which perfectly describes not merely his philosophy of life but his fulfillment of that philosophy.

"To live as gently as I can
To be, no matter where, a man
To take what comes of good or ill
And cling to faith and honor still
To do my best, and let that stand
The record of my brain and hand
And then, should failure come to me
Still work and hope for victory."

Robert S. Williams

WILLIAM EBENEZER FORD (1878–1939)

Fellow in Class II, Section 1, 1918

William Ebenezer Ford, mineralogist, was born in Westville, a suburb of New Haven, Connecticut, on the 18th of February, 1878. He was the son of William Elbert and Caroline Aby (Bishop) Ford. He attended the local schools and prepared there for college; and, entering the Sheffield Scientific School in the fall of 1896, graduated in June 1899. Following his graduation, he was appointed assistant in mineralogy to Professor Samuel L. Penfield, under whom he also carried on post-graduate studies in mineralogy and crystallography. In 1903 he received the doctorate and was thereupon appointed instructor in mineralogy. Professor Penfield's health failed him in the spring of 1900, and, although he was able to direct the research work of advanced students, the routine class work was in that year carried on by the writer, who was then serving as instructor in mineralogy. It is a pleasure to him to recall that Mr. Ford assisted him most efficiently in these duties. Although Dr. Penfield's health improved, the routine work of teaching was carried by Mr. Ford. In 1906, shortly before the lamented death of Dr. Penfield, Mr. Ford was promoted to be assistant professor of mineralogy. In 1920 Mr. Ford was made professor of mineralogy and a member of the Governing Board of the Sheffield Scientific School, which position he held until his death in March 1939.

In 1920 he married Mary Treat Jennings of Rochester, New York, who survives him. Both he and Mrs. Ford enjoyed entertaining their many friends and extended a delightful hospitality both at their home on Lincoln Street, New Haven, and, in the summer, on the Cape where they had a cottage. Mr. Ford was very fond of music, and was himself an accomplished pianist.

Ford was always an effective and successful teacher, and his courses were deservedly popular. His pleasantly informal and friendly manner of handling students, and the large amount of personal attention which he gave them, seldom failed to arouse a genuine interest in the subject he taught, which often continued in after years quite irrespective of the student's particular occupation in life. He was always interested in their personal problems and perplexities, and was regarded with an unusually warm and lasting personal affection by all of his students.

As might be expected of one trained under Dr. Penfield, Mr. Ford's scientific work was characterized by meticulous and thorough investigations covering the morphological, physical and chemical properties of minerals. Although he did not possess the almost uncanny skill and ingenuity as an analyst that was Penfield's, he had a thorough knowledge of chemistry and was successful in associating with himself in his laboratory several men, like Dr. Walter Bradley, who were accomplished analytical chemists, and he used the results of their work most effectively. Almost without exception, the results of his investigations were published in the American Journal of Science. His first paper (with Penfield) appeared during his first year of postgraduate study, and during the next twenty years he was the author, sometimes in collaboration with his associates, Dr. Walter Bradley or others, of fifty papers.

Among the more important of these may be noted one published in 1913 dealing with the optical properties of the amphiboles. Another paper appeared a year later which represented an exhaustive study of the garnet group. A third paper of note was a similarly thorough study of the rhombohedral carbonates. All three of these papers constituted valuable additions to our knowledge of important minerals, and all were primarily concerned with studying the relations existing between the chemical composition of the members of isomorphous mineral compounds, and their physical properties. The first one cited, that on the common amphiboles, was a completion and extension of an investigation begun by Dr. Penfield and F. E. Stanley. While the complexity of the chemical composition of members of this group of minerals made any very definite conclusions regarding the relations between the chemical composition and the physical properties impossible, he was able to show some degree of correlation between the mean indices of refraction and the percentage of the principal oxides present; there also appeared to be some correlation between the amount of total iron present and the value of the extinction angle. In his study of the garnet and calcite groups, respectively, he determined the approximate degrees of miscibility which the various mineral molecules exhibited, and showed that there existed a fairly close correlation between the chemical composition of a given isomorphous mixture, the index of refraction, and the specific gravity. He represented these relationships in a series of diagrams from which, if the values of two of these properties are known, the third can be determined with some accuracy.

At the time when the paper on the rhombohedral carbonates was being prepared, the results of Bragg's x-ray determination of the size of the unit cell and the atomic structure of calcite became available, and it was known that the crystal structure for dolomite, siderite and rhodochrosite must be of the same sort as that of calcite. Mr. Ford discussed this with special reference to the effect of isomorphism on the crystal lattice. He concluded that the lattice for all members of the group and their mixtures remained the same or with at most very small variations insofar as the atomic arrangement and crystal angles were concerned; that the only variation must therefore be in the spacing of the molecular layers which would of course involve a change in the volume of the unit cell. "Complete isomorphous replacement in all proportions would only be expected in the case of two molecules having naturally identical space lattices or with lattices that may change progressively from one end of the series to the other. In other instances the amount of replacement would be conditioned upon the similarity between the two lattices and would proportionally diminish in amount as this similarity decreased." His assembled data seemed to conform well with this theory.

For some years before the publication of the calcite paper in 1917, Mr. Ford had devoted considerable of his time to the work of editing and revising the Dana texts on mineralogy, and as time went on he gave almost his entire attention, not devoted to teaching, to such work. In 1909 the second appendix to Dana's System of Mineralogy was published by Mr. E. S. Dana and Ford, and the third appendix—1915—was entirely Ford's work. He was also the author of the revision of the 13th edition of Dana's Manual of Mineralogy published in 1912. In 1922 appeared under his authorship the third and revised edition of Dana's Textbook of Mineralogy; in 1929 appeared the 14th edition of the Manual; and in 1932, the very largely rewritten and much enlarged 4th edition of the Textbook. In particular, in this edition he had expanded and brought up to date the part dealing with crystallography, including a chapter on crystal structure.

The very great additions, both factual and theoretical, to mineralogical science that had been made since the publication of the sixth edition of Dana's System of Mineralogy in 1892, even with the supplement and the three appendices that had been issued up to 1915, demanded attention if the System were to maintain its position as an up-to-date book of reference. The preparation of a further appendix seemed quite inadvisable, and accordingly Mr. John Wiley of the Wiley firm which had published the Dana texts for over a long period of years proposed to Mr. Ford the project of preparing a new and complete revision of this great work. Mr. Ford agreed to act as editor-in-chief, and began in 1920 to lay out and organize the work and to collect material. Be it said to Mr. Wiley's credit that it was because of his very real desire to make an important contribution to mineralogy and geology, in which fields of publication his firm had for so long been preeminent, that he was led to propose this project. He had no thought that it would be a financially profitable venture. Indeed, it was likely to be quite otherwise, for it involved, besides the high cost of publication of a book of this type, the employment under the chief editor of other highly trained experts, and the certainty of a relatively limited market for its sale.

Mr. Ford associated with himself from time to time several men with chemical and mineralogical experience, and more particularly had secured the cooperation of Dr. Charles Palache of the Harvard laboratory to supervise the revision and expansion of the crystallographic part of the work. Considerable progress had been made in this really tremendous piece of work when Mr. Ford's health began to fail him, and he realized that additional assistance must be had if the work was to be carried on. He and Dr. Palache made an appeal to the Geological Society of America for aid and received a generous response in the way of a substantial grant of money. About two years ago Mr. Ford, because of his poor health, was obliged to turn the entire project over to Dr. Palache. While it was a great and bitter disappointment to Mr. Ford to have to relinquish a piece of work which he felt was to be the climax of his life's work at the Yale laboratory, he took comfort, as did all with a genuine interest in mineralogy, that the work of preparing the new edition of this standard work should fall to the most capable of all men for the task, Dr. Palache.

Besides his many investigations dealing with individual minerals and mineral groups, the contribution to mineralogical science for which Dr. Ford will be best and most gratefully remembered by teachers and students of the subject will be the valuable service which he rendered with such untiring patience and skill in editing and revising a series of texts that are widely used the world over wherever mineralogy is studied.

CHARLES H. WARREN

TENNEY FRANK (1876–1939)

Fellow in Class IV, Section 3, 1935

Tenney Frank was born in Clay Centre, Kansas, May 19, 1876, and died at Oxford, England, April 3, 1939. He was of Swedish parentage, and passed from the life of a small town to school in Kansas City and thence to the University of Kansas, from which he was graduated in 1898. His subsequent professional studies were pursued, under a group of distinguished classical teachers, at the University of Chicago, where he also was instructor in Latin from 1901 to 1904. There he received the doctor's degree in 1903. From 1904 to 1919 he served as associate professor and professor of Latin at Bryn Mawr College, whence he was called to the professorship of Latin in the Johns Hopkins University which he held until his death. These periods of teaching were punctuated by studies at Göttingen and Berlin in 1910–11 and by various lectureships, at Bryn Mawr College in 1929, the University of California in 1929–30, Oberlin College in 1931, the British Academy in 1931–32, and Oxford University at the time of his death, as well as by service as professor or director of the American School of Classical Studies in Rome in 1916–17, 1922–23, and 1924–25.

Frank's untiring energy appears in the large bulk of his published work. A list of these publications in *The American Journal of Philology* for July, 1939, includes fifteen books—several of them of considerable size, and some of them also published in Italian translation—and over a hundred and fifty periodical articles, not to mention reviews in professional journals. From the rather purely grammatical studies which characterized his earliest period and which were prompted by teachers primarily interested in grammar, he soon passed to his more continuing interests, namely, Roman history and the criticism and elucidation of the greater classical Latin authors, such as Plautus, Terence, Catullus, Cicero, Virgil, and Homer. Though these were both familiar fields, Frank could never be content merely to retrace ground already traversed by others, but his well-stocked mind was ever alert to recognize fresh aspects and to point out untried possibilities. Not all his theories, of course, will stand the test of time, but his additions to our permanent knowledge have been large and important, and his writing is always stimulating to the search for truth. Well acquainted with various other fields, he often brought from distant areas keys to unlock unfamiliar doors to the classical world. This may be illustrated in his employment of mineralogical criteria for the dating of Roman buildings, and in his crowning work, well advanced at the time of his death, the *Economic Survey of Ancient Rome*, of which four volumes by him or by collaborators under his editorship have already appeared, a fifth being in progress. As editor of *The American Journal of Philology* and an associate editor of *The American Historical Review*, Frank had large influence upon philological and historical studies, and the esteem in which he was held is evidenced by his election as fellow of the British Academy, the Swedish Royal Society of Letters, and our own academy, as well as by membership in the American Philosophical Society, the presidency of the American Philological Association, and the degree of L.H.D. awarded him in 1938 by Union College.

In 1907 Frank married Grace Edith Mayer, a Romance scholar well known for her own work, whose companionship brought strength and finish to his own labors and joy in his avocations of outdoor life and natural history.

Professor Frank, by friendly helpfulness, enthusiasm, and an unusual mingling of personal modesty and intellectual daring, firmly attached to himself both pupils and colleagues. His accomplishment was large and much of it of a pioneer sort, and few American scholars in the fields he cultivated are so often or so respectfully cited by the scholars of other lands.

Arthur Stanley Pease

EDWARD GARDINER GARDINER
(1854–1907)

Fellow in Class II, Section 3, 1891

Edward Gardiner Gardiner represented the best in New England tradition. His ancestry included George Gardiner who settled at Aquidneck (now Narragansett), Rhode Island, about 1635, and Dr. Sylvester Gardiner, great-grandson of the first settler, who moved to Boston before 1750 and achieved some eminence as a physician and surgeon and whose descendants were prominent in the General Court, in the Church, and at the Bar. Another ancestor was Thomas Handesyd Perkins, a prominent East India merchant.

His father, Edward Gardiner, was an architect, devoted to the high ideals of his profession and a keen sportsman delighting in hunting, dogs, and horses. At first a civil engineer, taking part in the construction of the Connecticut River Railroad, he soon turned to the profession of architecture, which took him to Philadelphia, where he married Sophia Harrison Mifflin, daughter of Samuel Mifflin, one of a distinguished Philadelphia family. From there he moved to New York and built a summer home at New Rochelle, where his second son, Edward Gardiner Gardiner, was born July 29, 1854, There he prospered until the panic of 1857 halted all building. He was killed by a fall from a horse while on a journey to the West in 1859. Whereupon his wife with her five young children came to Boston to make her home among her husband's people.

Her son Edward was a peculiarly sweet tempered and affectionate child. At the Boston Latin School he was preparing for Harvard when trouble with his eyes cut him off from all studies for several years. During this period an inclination toward outdoor life, inherited from his father, led to solitary rambles in the country during which he developed a taste for life in the woods. His scientific career began when he became acquainted with Alpheus Hyatt, then Curator of the Boston Society of Natural History and Professor of Zoology and Palaeontology at the Massachusetts Institute of Technology; and helped him in sorting zoological material at the Society's museum. Later he accompanied Hyatt on repeated cruises along the coast as far north as Labrador, taking his turn in navigating the schooner as well as in the collection of zoological material, and hugely enjoyed both his nautical and scientific experiences. His warm affection for Professor Hyatt and his interest in zoology led him to enter the Institute of Technology, at first as a special student—all that his eyes would permit. Later he became a regular student and in 1882 graduated with the degree of S.B. in Natural History.

He had been in Europe with his grandfather's family in 1874, spending some months in England. On his second trip to Europe following his graduation, he joined the throng of students that was flocking to the laboratory of Rudolph Leuckart at Leipzig. While a student of chick embryology under Hyatt he had been interested in the development of a horn-like elevation on the embryonic beak. Under the direction of Leuckart he expanded this study into a detailed investigation of the development of the epidermis and of the beak of birds. His results were embodied in a dissertation that was published separately in 1884 and also in the *Archiv für mikroskopische Anatomie* (**24,** 1885), and in 1884 he was admitted to the Ph.D. degree.

On his return to Boston, now a trained zoologist, he was welcomed in the laboratory of Professor W. T. Sedgwick, then struggling to build up a newly established Department of Biology at the Institute of Technology. Thus began a life long friendship and intimacy between the two men. In 1885 Dr. Gardiner was appointed Assistant, and in 1887 was promoted to Instructor in Zoology. His interest in zoology and in outdoor life led, not only to collecting trips at the seashore, but also to hunting trips in Maine, and to his association with a group of friends in the founding of the Myopia Hunt Club, so called because all the founders were nearsighted.

In 1887 Gardiner took part in an event that was to have far reaching results. It was a meeting to consider a permanent basis for the sea-side laboratory that for several years had been maintained at Annisquam by Professor Hyatt under the auspices of the Woman's Education Association of Boston and the Boston Society of Natural History. This meeting led to the founding of the Marine Biological Laboratory at Woods Hole, with Dr. Gardiner as one of the incorporators. Following the incorporation on March 20, 1888, he was elected to the Board of Trustees together with Professors Hyatt and Sedgwick, W. G. Farlow, Susan Minns, C. S. Minot, and Samuel Wells. He soon withdrew, however, in favor of Miss Florence M. Cushing, who also was active in promoting the organization.

When the Laboratory was opened at Woods Hole, July 17, 1888, under the direction of C. O. Whitman, Gardiner was one of seven investigators to occupy a table. The next year he was appointed Instructor to supervise beginning investigators in need of assistance, and in 1890 he was elected again to the Board of Trustees—a position he held the rest of his life—and he remained on the instructing staff during the summers of 1890 and 1891. During these formative years he was one of the chief supporters of the Director, always ready to help when needed. When in 1890 a steam launch was purchased in Boston, he navigated the boat on its dangerous voyage around Cape Cod to Woods Hole. While not in charge of instruction to students, he frequently lectured to the class and he was one of those called upon for evening lectures before the larger assembly. His own field of investigation was the embryology of compound Ascidians until 1891, when he turned his attention to acoelous Turbellarian worms.

While always a devoted friend of the Biological Department of the Institute of Technology and of its head, teaching had become irksome to Gardiner, and he withdrew in 1892 to give more time to his original work at Woods Hole. The first published result appeared in 1895 in the *Journal of Morphology* (**11,** 155–171). In this paper on the "Early Development of Polycoerus caudatus, Mark," he described the egg and traced the cell-lineage from the first cleavage to the 66-cell stage of this acoelous Turbellarian, and he gave the first published pictures of the remarkable bilateral cleavage stages in this group of worms.

In April 1895 Dr. Gardiner was married to Miss Jane Greene Hooper of Boston, and soon after he built on a knoll overlooking Buzzards Bay a house that has been the summer home of his family ever since. Early in 1894 the growth of the Marine Biological Laboratory had called for a new building to house the botanical department, and when in the spring of 1895 the Trustees found themselves unable to provide the necessary funds, Dr. Gardiner, then a member of the Executive Committee, supported the Director, and, at considerable personal inconvenience, shouldered the whole burden of loaning the money required for the building and its equipment so that it might be completed at the beginning of the summer session. That year he was elected Clerk of the Corporation, a position he held, together with membership on the Executive Committee of the Trustees until 1902 and from 1906 to the end of his life. He was also Secretary of the Board of Trustees from 1896 to 1902.

Gardiner's second paper on Polycoerus appeared in 1898 (*Journal of Morphology,* **15,** 73–110). Here he described, with excellent illustrations, the cytological processes in the egg from the time of entrance of the sperm to the beginning of the first cleavage. During the winter of 1898–99 Gardiner was at Plymouth, England, engaged in the study of the British Rhabdocoels, another branch of the Turbellarians. He found the Laboratory of the Marine Biological Association a most delightful place to work, and he enjoyed the social opportunities, especially hunting with the otter hounds. In February, 1900, he made a trip to study the fauna of Porto Rico accompanied by Admiral Grinnel and G. M. Gray, who collected much zoological material. The winter of 1902–03 found him again at Plymouth, where he stayed into the summer, continuing his work on the Rhabdocoels.

But the monograph that Gardiner had projected was never completed. He again had been elected Secretary to the Trustees of the Marine Biological Laboratory only three months before a brief illness was ended by his death in Boston, November 4, 1907. Thus abruptly were terminated his scientific studies and his administrative activities, and the Trustees suddenly were deprived of his valuable and efficient services. At that time he was the only original member remaining on the Board, where his long connection with Laboratory affairs and intimate knowledge of its history made him one of the most important members; and his high standing in Boston enabled him to secure valuable assistance for the promotion of the aims of the Laboratory. He had lived to see the Laboratory grow from eight students and seven investigators in 1888 to 47 students and 60 investigators in 1907; and the greater success that followed was to be the fulfillment of his life interest. He was a man whose fine sense of honor and loyalty was shown in his deeds, and the many friendships that he cherished were warm and enduring.

R. P. Bigelow

EDWIN HERBERT HALL (1855–1938)

Fellow in Class I, Section 2, 1883

Edwin Herbert Hall was born in North Gorham, then Great Falls, Maine, on Nov. 7, 1855, the son of Joshua Emery Hall and Lucy Ann Hilborn Hall. He was descended from John Hall, who came to this country from England early in the 17th century, from Anthony Emery, a Huguenot, who landed in Boston in 1635 and from Kenelson Winslow, who immigrated to this country about 1629. For two generations back his ancestors were Maine country folk, sound citizens of the New England type.

Young Hall attended the usual district schools and prepared for college in two years at "Gorham Seminary." He entered Bowdoin before he was sixteen and graduated four years later at the head of his class in 1875. For two years thereafter he taught school. He then turned to science. He writes "I should perhaps have studied law, if I had not felt myself unfitted to advocate a cause in which I did not believe." This quotation is well worthy of note for it is most characteristic of the man.

In the fall of 1877 he entered Johns Hopkins University as a graduate student in physics under Rowland. It is rare that a youthful student entering the field of research scores a bull's-eye as a result of his first investigations. But it was so in Hall's case for in 1879 he discovered the "Hall Effect." The happy result cannot be attributed to good fortune. It must be held as evidence of the skill and persistence of the student and of the vision of his instructor, Professor Rowland. This "Hall Effect" is usually described as a difference of potential which appears perpendicular both to the lines of flow of an electric current and a magnetic field, the magnetic field itself being perpendicular to the current. Hall's thesis contained a quantitative measurement of the effect in gold for various current strengths and for different values of the magnetic field. The importance of the matter may be judged by some remarks made by Lord Kelvin at a meeting of the British Association in 1881, at which Hall read a paper on his discovery—"The subject of the communication" said Kelvin, "is by far the greatest discovery that has been made in respect to the electrical properties of metals since the times of Faraday—a discovery comparable with the greatest made by Faraday." Here then was Hall, at the age of twenty-six, placed in the company of one of the greatest of physicists!

But he had his living to make. In 1881 he was appointed instructor in physics at Harvard, he was assistant professor from 1888 to 1895, professor from 1895 to 1914, Rumford Professor from 1914 to 1921 and Emeritus Professor from 1921 till his death. He grew up with the Department and contributed greatly to its strength and reputation. He received his Ph.D. from Johns Hopkins in 1880 and an LL.D. from Bowdoin in 1905. At the time of his death he was the second in seniority among the Fellows of the American Academy of Arts and Sciences, having been elected in 1883; he joined the National Academy in 1911. He was a member of the Solvay Congress at Brussels in 1924 and of the Volta Congress at Como in 1927. In 1937 he received the medal of the Association of American Physics Teachers for Notable Contributions to the Teaching of Physics.

On August 31, 1882, he married Caroline Eliza Bottum.

Hall's technical contributions fall into two groups. We have seen that he began his career with a great discovery. His second contribution was in a different field, it was not so brilliant but not less important. For through his efforts the teaching of physics in our primary schools, which up to that time had been in a very unsatisfactory state, was greatly improved and placed on a satisfactory basis. All this was not brought about without much sound thinking, and hard work. The result will always stand as a monument to the subject of this notice.

As a university teacher he gave courses in elementary physics for many years and courses in thermodynamics and kinetic theory to more advanced students. His teaching was marked by clarity and thoroughness. No difficulty was ever glossed over; it was followed up and dissected in the most careful manner. He had a very real concern that the listener should understand the situation.

The number of his research students was not large, perhaps not more than a dozen altogether. He took a keen personal interest in them and was rewarded by the strong affection which they all felt for him.

Of course Professor Hall will always be best known by the "Hall Effect" and the major part of his scientific activity as an experimenter and as a writer was connected either directly with this subject or else with closely related matter, including the theory of the flow of the electric current in conductors. He continued working with his own hands at his research with undiminished enthusiasm till the end of his life. In fact, within a few weeks of his death, he was planning new experiments in a new field.

In order to obtain an idea of the extent, variety and value of Professor Hall's work the reader cannot do better than to look over the titles of the 109 papers which he published between 1879 and 1938.

He died in Cambridge, November 20, 1938.

Valuable as were Professor Hall's contributions to the teaching of physics throughout the country, and important as were his contributions to science; it was for the beauty of his character that he will be best remembered by those who knew him well. He was a man of the very highest principles and of unswerving rectitude. But his attitude toward others was marked by charity and a gentle humor. Active in his civic duties—he served during the Boston police strike—no appeal from a good cause went unheeded by him. He was a religious man but he never thrust his convictions on others. He sustained with fortitude illness and family affliction and emerged serene and happy. The community is the better for his example, for he was indeed a most admirable citizen.

THEODORE LYMAN

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ELMER PETER KOHLER (1865–1938)

Fellow in Class I, Section 3, 1914

The passing of Elmer Peter Kohler, Sheldon Emery Professor of Organic Chemistry at Harvard, brought to a close a highly distinguished career of service by a man of unique qualities and altogether rare personality. While others who have made a mark in American science have been properly acclaimed for their inspiring teaching, brilliant research, or leadership, tribute to Kohler on all of these points seems so obviously justified as to constitute merely a starting point for an attempt to draw an adequate characterization. To those who knew Kohler, his accomplishments were largely a matter of course. He was endeared to his friends and students not so much for what he achieved but for the special, unique and unpredictable way he had of doing things. The unusual character of the man is perhaps indicated most strikingly by the fact that although he attended no society meetings, wrote no books, and never delivered a public address, he exerted a profound and quietly dominating influence on the development of American chemistry. This position of importance was not of his own seeking but came to him in natural and logical recognition of his ability, sagacity, and abundant humanism.

Certain of his endearing personal characteristics carry the distinct flavor of Kohler's Pennsylvania Dutch heritage, of which he was immeasurably proud. Born on November 6, 1865, in the village of Egypt, Pennsylvania, he spent his early years at the homestead which had been in the Kohler family for several generations and he retained throughout life the keen interest in farming and in country life gained in this formative period. Plainly engraved in his character was the traditional frankness, frugality, and friendly humor of the farming folk of the Lehigh valley, and his inborn taste for simple and natural ways of life never left him. His ancestor Jacob Kohler had emigrated from Mühlhausen, Switzerland, in 1728 and, as the first settler in the vicinity, had acquired a large tract of fertile land by warrant from the Penn Heirs. Succeeding generations of Kohlers remained in Egypt as successful farmers, millers, and merchants, and young Elmer in turn learned the methods of farming and acquired a mastery of practical mechanics from working in the mill and with the machines on his progressive father's farm.

Kohler attended the nearby Muhlenberg College at Allentown and in 1886 graduated with honors from the classical course. After graduation he decided to seek a career in the west, and on stopping at Kansas City in quest of employment he encountered in a downtown ticket office a clerk who had come from his Pennsylvania Dutch country. This friendly association gave him an opportunity which he lost no time in seizing. Left for a short time to keep watch on the office, he had an inquiry regarding transportation for a large family to a remote town in Oregon. This required routing over various rail and stagecoach lines under special conditions accorded to western settlers, and presented a problem of considerable difficulty. Although he had neither training for the task nor authorization to make a transaction, Kohler calmly planned the route, made out the complicated tickets, and accepted payment. The ticket agent on his return was at first scandalized, but on discovering that the job had been done to perfection and without a slip he was so impressed with Kohler's ability that on his recommendation Kohler very shortly was given a regular appointment as special passenger agent with the Atchison, Topeka, and Santa Fé Railroad. In this position his assignment was to recruit groups of farmers and their families from the Lehigh Valley region and settle them in the western country along the Santa Fé.

This early experience in railroading was to be of good use many years later. At the outbreak of war in Europe in 1914 Kohler set off without delay to see what he could of the way in which a modern army is mobilized. Disregarding inevitable discomfort and inconvenience he spent some time in Innsbruck before being obliged to make a hurried retreat to Switzerland and thence to England. While waiting in London with countless others for passage home, he formed the habit of meeting incoming trains which were bringing increasing numbers of stranded Americans from Paris. Each time, Kohler would single out a few of his more distressed fellow countrymen and help them find accommodations and the ways and means of returning home. Eventually this unostentatious work came to the attention of a British Army officer assigned to this very duty and, noticing that Kohler's quiet methods were far more effective than his own, he urged Kohler to postpone his return and accept appointment as special agent to expedite the evacuation of neutrals from the war area. In consequence, Kohler for some weeks prior to the opening of the college year found himself journeying back and forth between London and Paris applying practical knowledge gained in youth as a travelling passenger agent on the Santa Fé.

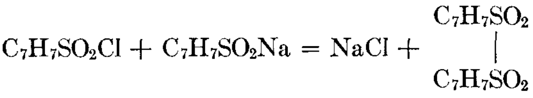
While his early work with the railroad was agreeable and interesting, Kohler before long decided to extend his studies, and after taking the A.M. degree at Muhlenberg in 1889 he entered Johns Hopkins University and took a research problem under Ira Remsen. In this period Hopkins was the leading center in the country for graduate study and research in chemistry, and Kohler made many friends in this stimulating environment. Remsen's discovery of saccharin was but a decade old and he was still exploring the chemistry of orthosulfobenzoic acid derivatives. Kohler's work for the degree under his much admired master was in this field and involved a study of the action of aniline on the interesting chlorides of the acid. Making rapid progress, which in later years he attributed largely to the generous coaching of his good friend H. M. Ullmann, later Head of the Department of Chemistry and Chemical Engineering at Lehigh University, he completed his research and took the Ph.D. degree in 1892.

Kohler's first appointment, which he received immediately following the completion of his work at Hopkins, was to the faculty of Bryn Mawr College, where he was to remain for twenty years. Starting as instructor, and as the first teacher of organic chemistry at Bryn Mawr, he soon became recognized as a scholar of the first order and a teacher of rare ability, and he advanced steadily and attained a professorship in 1900. Advanced students and beginners alike found in Kohler a stimulating lecturer, an exacting master satisfied only with experimental work of the highest quality, and a man of great personal charm. He exerted considerable influence in the college as a whole, and for many years he not only held the position of head of the chemistry department but was recognized as an informal counsellor to the dominating president, Miss M. Carey Thomas. It was said, indeed, that Kohler was one of the very few individuals from whom the president would accept criticism, and there probably was a close bond of understanding between the two strong and determined personalities. The story is told that on the departure of Professor Keiser for a post at Washington University, President Thomas asked Kohler's advice about the appointment of a successor as head of the department. Kohler in reply stated frankly that he thought himself to be the proper successor, saying "If you can find and attract a better man than Elmer P. Kohler, I shall continue to work here and work with him cheerfully, but if, in my opinion, he is not a better man than I am, you will have my resignation." The appointment went to Kohler.

Some five years elapsed before Kohler's activities in research bore fruit in the form of a publication, his first independent paper appearing in the American Chemical Journal for 1897. The brief delay, however, was due to a piece of bad luck, for his first investigation was anticipated by Victor Meyer. This work was on the alpha-bromination of alkyl bromides in the presence of metal halides, and Kohler had established to his own satisfaction that the reaction proceeds through an elimination—addition mechanism at the very time of the appearance in 1892 of the first of Victor Meyer's classical papers on the subject. Recognizing that a lone and unknown worker could hardly compete with the distinguished German and his corps of assistants, Kohler promptly abandoned work on the problem and sought a field which he could make distinctly his own. This he was not long in finding. The initial papers on aliphatic sulfonic acids (1897–1899), in which considerable attention was given to the chlorides of these acids, bear evident flavor of his dissertation work with Remsen but are characterized less by the nature of the starting point than by the originality of the attack.

This first work abounds in evidence of the touch of a remarkably gifted experimentalist and of the insight of a keen and thoughtful observer endowed with an uncanny faculty for appreciating the significance of seemingly trivial phenomena. In his paper with Margaret B. MacDonald of 1899 the discovery of the α-disulfones and α-ketosulfones is described as follows:

"Among the reaction-products of perfectly pure aliphatic and aromatic sulphone chlorides with a variety of reagents, we have frequently observed a minute quantity of some sulphur compound, that, owing to its insolubility in water, generally forms a scum on the surface of the liquid used. The insolubility of the substance, its stability on heating, and its inertness to reagents, pointed to some kind of sulphone, while the fact that the same substance or similar substances are obtained in a great variety of reactions indicated that only the sulphone chloride is involved in its formation. In the investigation above referred to we noticed that a substance of this kind was formed only in those experiments in which there was protracted heating and an insufficient amount of base. This suggested that the substance might be a disulphone formed by the interaction of a sulphone chloride and a sulphinate:



$$C_7H_7SO_2Cl + C_7H_7SO_2Na = NaCl + \begin{matrix} C_7H_7SO_2 \\ | \\ C_7H_7SO_2 \end{matrix}$$

We have found that this reaction gives a simple and, apparently, a perfectly general method for the preparation of disulphones of this kind."

A similar keen observation concerning a by-product was responsible for the discovery in 1908 of the first free radical having but two aryl residues joined to the trivalent carbon atom.

The passage quoted above is illustrative of Kohler's direct and clear style of writing. He always said that he disliked the laborious process of preparing a manuscript, but even though he bent himself reluctantly to the task the results stand as a joy to the reader. He had a keen critical judgment and seemed neither to miss points of significance nor to push his arguments beyond the limit of secure evidence. Kohler's papers from first to last are masterpieces of logical exposition; one reads them easily, and with complete confidence in the mature judgment of a true authority.

The special interests which eventually led to Kohler's classical work on unsaturated systems were perhaps germinating during the Hopkins period. In the work which he dropped in deference to Victor Meyer, he had recognized the importance of an ethylenic intermediary in the reaction and had become interested in the catalytic function of metallic complexes. His first published paper described a general method for the preparation of α, β-unsaturated sulfonic acids, and in subsequent work he gave particular attention to the study of various addition reactions of these unsaturated acids. He did not immediately go over to the investigation of α, β-unsaturated carbonyl compounds, but was led into this important field in a fortuitous manner. Interested not only in additions to unsaturated compounds but in the modifying influence of unsaturation on other functional groups, he set out in 1903 to synthesize diphenylstyrylcarbinol (B) in order to explore the gap between the highly reactive triarylcarbinols and the widely different tertiary alcohols having one alkyl and two aryl groups. From all that was known at the time the synthesis which he selected should give a substance of the desired structure (B), and the product obtained responded satisfactorily to a

$$C_6H_5CH = CHCOC_6H_5 + C_6H_5MgBr \rightarrow \quad (A)$$
$$C_6H_5CH = CHC(OH)(C_6H_5)_2 \quad (B)$$

number of diagnostic tests and degradative experiments. There were certain peculiarities, however, which bothered him, and he sensed a certain discrepancy between the observed properties of the compound and the expected behavior. He set out to allay these suspicions and in the following year succeeded in proving conclusively that the product obtained from benzalacetophenone and phenylmagnesium bromide is not diphenylstyrylcarbinol (B) but β, β-diphenylpropiophenone, $(C_6H_5)_2CHCH_2COC_6H_5$, thereby discovering a new mode of addition to α, β-unsaturated ketones. In the first paper (1904) on this important subject Kohler states that "The facts at present available are not sufficient to make it possible to decide, conclusively, between the two formulas (for primary 3,4- or 1,4-addition), but I believe that Formula II (1,4-addition) gives the simplest explanation of all the reactions that have been studied." One is tempted to venture the guess that, thirty-four years later, after the accumulation throughout the whole chemical world of a great body of experimental observations and theoretical speculations concerning additions to conjugated systems, Kohler would have been content with the same statement of the case.

The discovery of the new type of addition reaction opened a wide field, and Kohler lost no time in seizing the opportunity offered. With an increasing number of competent collaborators he was able to push the investigation of conjugated compounds in many directions, and the work as a whole constitutes a major contribution to organic chemistry. His transfer to Harvard in 1912 was followed by a considerable expansion of the research program, for more and more students were attracted to the laboratory of this able investigator. He studied the peculiar form of unsaturation encountered in the three-carbon ring and explored the properties of cyclopropane ketones analogous to the α, β-ethylenic compounds, he included unsaturated substances of the carbocyclic and heterocyclic series in the scope of the work, he studied oxides and lactones having adjacent carbonyl groups, he made comprehensive studies of the necessarily related problems of the tautomerism, isomerism, and configuration of unsaturated compounds, and in short extended his inquiry on unsaturation in all manner of different directions. Any brief appraisal of Kohler's scientific contributions is entirely inadequate, and one can only quote the generally current opinion that the work was truly monumental. It is interesting that in his later years he returned to an early love in the form of the sulfones, investigating in 1935 sulfones having an adjacent ethylenic linkage. Also of interest is the fact that among his first papers from Harvard are those on the chemistry of cyclopropanes, while his latest work, at which death overtook him, was in the field of large-ring cycloparaffins. The first publication on cyclopropanes was with his student J. B. Conant, who later took time from his affairs as President of Harvard to direct the work of completing the researches on higher cycloparaffins which Kohler had undertaken just two years before his death.

Kohler was appointed to a professorship at Harvard in 1912, became Abbott and James Lawrence Professor in 1914, and Sheldon Emery Professor in 1934. To the sheer delight of beginning students, he conducted for several years the introductory course in elementary chemistry. While he excelled in the art of evolving the fundamental principles in a most stimulating way, his special contribution to methods of higher education was in his famous Chemistry 5, a course of advanced organic chemistry. This course was predominantly theoretical, rather than descriptive, and covered such topics as tautomerism, unsaturation, conjugation, addition and substitution, structure, and configuration. One distinctive feature of Chemistry 5 was the beautifully logical exposition, for the subject seemed to unfold and expand in a manner which in retrospect seemed to the listener to have been truly inevitable, and there are many who treasure their year in the course, quite apart from the technical information gained, as a rare experience in the realm of pure reasoning. Another quality which Kohler instilled into Chemistry 5 was the spirit of active participation by the student in the unravelling of the theme. At intervals, and only when an entirely suitable occasion arose, the lecturer, having developed a background and presented a certain set of facts, would pause with a gleam in his eyes and ask the class what theoretical inferences could be drawn. Any one had a right to speak and any opinion was given whatever consideration it merited. Although we always imagined that the conclusion reached by the group as a whole was no surprise to the lecturer, we invariably had the feeling that the question was honestly put, that anything might happen on the momentous occasion of concerted thought, and that the lecturer was entirely open minded and would promptly recognize any new idea which might develop. This was teaching, and a man who could elicit such a response in his students must have had many a quiet chuckle of satisfaction. To Professor Kohler Chemistry 5 was sacred ground, and he would countenance no abuse. Idle visitors were excluded, whether they were research fellows, younger members of the faculty, or visiting professors, for students were not to be restrained or embarrassed by the presence of those who might have been over some of the ground before.

Kohler used no notes in lecturing, except for an occasional card which he would produce from his pocket for the citation of a table of figures. His material was always perfectly organized, and neatly timed to begin and end on the stroke of the clock; his delivery seemed very easy and natural, and indeed he was a truly magnificent speaker. Strangely enough, he could not be persuaded to accept any outside speaking engagements whatsoever, and even professed to dislike lecturing and stated that it put him under considerable strain. He told one of his former assistants that before every lecture he had the same hollow, sinking feeling which he had experienced at the time of his first college lecture, but that this left him once he started talking. Aside from such of his pupils in whom he had confided or who inadvertently had tried to approach him before a lecture, no one could have guessed that he was nervous before speaking.

The legendary belief that he destroyed his notes each year and made fresh ones has been fully verified. The night before a Chemistry 5 meeting he frequently wrote out his lecture, or a considerable part of it, in neat longhand. The sheaf of papers was then pushed into a drawer of his desk without any classification, and these notes apparently were allowed to accumulate until summer and then discarded. In his long years of teaching, this practice was never abandoned. Certainly Chemistry 5 was different each year. There was a definite continuity, and yet it was evident that the old material each time had been considered afresh, along with any new work having a bearing on the problems under discussion. Few men of any age group have had the energy to keep abreast of the times as Kohler did. He was eternally young, always ready to abandon earlier concepts in the light of new developments, always interested in making full use of the contributions of physicists and physical chemists to the knowledge of organic compounds.

The laboratory work of Chemistry 5 was also unique, and many consider that Kohler's system of problem work is a fine example of the tutorial method of instruction at its very best. During the second semester students whose previous work had placed them in about the first third of the class were permitted to apply for a problem. They were by no means handed a problem or forced to undertake special work; on the contrary each man had to appear for a personal interview and support his claim to special consideration, and under the shrewd scrutiny of the professor a supposedly bright record of undergraduate attainment often seemed to fade to something of little significance. Entrance to the problem group, furthermore, was only a start on a long road of humbling self revelation. We were all given individual problems personally directed by Professor Kohler, and we started off on our respective ways with great glee and enthusiasm. It was fun to be a scientist and do real research, and some of us ran through the whole problem outlined on the very first day. The next day in consultation we learned that that had not been research but nonsense, and we spent the next few weeks trying to work out the first step of the process. As time went on we gradually began to get some insight into the nature of scientific investigation, we learned to have respect for the difficulties and obstacles, and we perhaps caught a glimpse of the fascination of true research. By the end of the year some men in the problem group had gained an inspiration for a life's work, some had come to see that the temperament and talent of a research worker was not theirs, and we all had had a unique experience enriched above all by personal contact with one whom we admired immensely as a man and whom we respected as a great master.

There was a rare but not easily defined quality in the association which grew up between Kohler and most of his research students. With very few exceptions his pupils in later years cherished for him an intimate and personal affection which was almost filial, and yet these same men could all recall occasions when they had regarded him with the greatest awe and they could narrate first hand instances of the somewhat sharp and caustic way he had of offering criticism. Those who learned to know Kohler eventually found that his occasionally vented criticism left no sting. For one thing, whatever objections he may have raised usually became recognized as entirely sound and very much to the point. That his remarks sometimes seemed sharp may have been because of their utter frankness. He had no use for sentimentality or indirectness, and he did not hesitate to speak the plain truth as he saw it. Because of this honesty of expression, coupled with a critical faculty which was truly remarkable, Kohler brought forth from his students the very finest type of intellectual effort. To give a colloquium talk in which Kohler would see no loose points or weak arguments was regarded by graduate students as the highest possible achievement. That unforeseen criticism usually was forthcoming, and that it had to be accepted as justified, merely made the goal all the more worth working for.

While Kohler's frank and somewhat abrupt ways became recognized by his older students as an interesting and understandable phase of his personality, beginners in research often were a little terrified by him. Whether he did it deliberately or not, his manner with these men usually was such as to put them on their mettle and to goad them on to the best efforts of which they were capable. One former Chemistry 5 student who is now a professor recalls that at an interview Kohler suggested his taking a preparation rather than a problem, saying, with obvious implications, "You are not going on in graduate work, are you?" Although the student had planned to seek employment in the industry at the end of the year, this remark offered such a challenge that he insisted upon a problem and before long decided to work for the Ph.D. degree. Another man, who took Chemistry 5 in his junior year, related the following incident:

"I had the usual interview with Kohler in which we discussed the problem, then checked in and prepared the material and carried out the first reaction which he had suggested. Since I was an undergraduate taking the work without credit, I had assumed that Professor Kohler would use me pretty much as an additional pair of hands, and consequently, when I had done everything we had discussed, I sat around waiting for him to come through the laboratory. He did, and I made my report. Then he asked what I was going to do next. I said I did not know. At that he turned on his heel and told me I could get in touch with him when I had some ideas."

Those who came through such trials by fire as happened to be imposed upon them later learned to appreciate that the unusual experience, however nettling it had seemed at the time, had been the source of true stimulation. They also came to realize that what sometimes seemed like harsh treatment had been meted out with intent which was entirely benevolent but simply stripped of all sentimentality. Kohler certainly had the interests of his students at heart at all times, but his kindness was of a robust nature which admitted of no softness and of little direct expression. It was only years later that certain of his Ph.D. students discovered that their rather stern master returned some of the personal affection which they felt for him. Others recognized this quality at an earlier stage merely because of the staunch support which he had given them in meeting some emergency. He was deeply concerned in matters pertaining to the health of his students, or to their personal problems and even intimate family affairs, and on all such questions he could be turned to for valuable advice and help. He frequently helped students meet the difficult problem of financing the long period of graduate training, and he handled such matters with great understanding and wisdom. On one occasion he was given a rather considerable sum of money for the specific purpose of enabling one of his promising students to complete his studies for the Ph.D. degree. Kohler decided that it would be best for the man if the money were advanced as required in the form of a loan, rather than given outright and, with the consent of the donor, he followed this plan. The student graduated and in due course the loan was repaid. Kohler then proceeded to loan the money in the same way to half a dozen other students in succession, and finally arranged for the transfer of the grant, with some accumulated interest, to a research fund being raised at another university to support the good work of the original recipient of this rather unique fellowship.

In directing research Kohler had the faculty of guiding the work into profitable channels while placing as much responsibility as possible on the shoulders of the student. His concern to foster originality and independence bore such fruit that he left behind him a long succession of men and women who attained prominence as investigators. One learned many things from this master concerning the principles, methods, and techniques of the science, and one caught something of the enthusiasm and love for research which he kept ever fresh from continued experience. Kohler never gave up doing experimental work with his own hands, and to the end of his career he continued to spend such time as he could find working faithfully and joyfully in the laboratory. True it is that as a bachelor he doubtless had some hours for personal research not available to other scientists of comparable teaching and administrative commitments, but it is also true that he gave himself an unusually meagre allotment of time for relaxation and the indulgence of personal pleasures. Keen interests in the arts and letters, in current affairs and in nature were not allowed to occupy him unduly. He took but a short vacation each summer but, characteristically, he made his relaxation thorough. Going off for a walking trip in the mountains or "to paint the barn," he either left no forwarding address or gave careful instructions that he was not to be approached. When any pressing business was likely to require his attention he would simply remain in Cambridge and forego a vacation. Whatever happened he maintained his tranquility, for he seemed able to take the affairs of an active life at an easy stride and to conserve his abundant energies. According to student legend, once a day was often enough to examine mail, and he would answer only a limited number of telephone calls. Not infrequently, however, the occasion arose when he was in the mood to squander any amount of time for a discussion of chemical phenomena. When a visit from a colleague, assistant, or former student found him in his laboratory or in contemplation of recent experimental observations he liked nothing better than to outline the facts of the case and ask his visitor to try to interpret them or to predict the course of some reaction. This sometimes led to a discussion of the most interesting ramifications, or prompted Kohler to bring forth some of his rare stories and experiences, which he would relate with expansive detail and with great relish and effectiveness.

As at Bryn Mawr, Kohler at Harvard was drawn upon for much counsel on administrative matters. For many years he was a member of the Administrative Board of the Graduate School, and in 1926 he reluctantly took time from his researches to serve as Acting Dean of the Graduate School in the absence of Dean Chase. In 1934 he took over the chairmanship of the Division of Chemistry and guided the affairs of this body with great wisdom, insight, and fairness. During 1937–1938 he very reluctantly agreed to accept appointment to the committee investigating the Walsh-Sweezy case, and there were many who looked particularly to Kohler for a calm and mature judgment on the matter; unfortunately he did not live to record his opinion. Among other activities, Kohler served on the board of directors of the Harvard Coöperative Society and on committees of the Division of Medical Sciences and the Division of Biochemical Sciences. Outside the University, he for a number of years took an active part in the work of the committee on fellowships in chemistry of the National Research Council. During the war Kohler was called to Washington and placed in charge of research in the Offense Section of the Chemical Warfare Service of the United States Army. Although this branch of the Army's work had been in a state of great confusion, Kohler by virtue of his wide knowledge, his sense for the practical, and his robust leadership rapidly organized the Offense Section into a powerful and efficient unit. Still serving as a civilian, for he declined a proferred commission, he was later sent to Europe as a special observer to represent the Chemical Warfare Service in the inter-allied conference on chemical warfare. Granted leave of absence from Harvard for this service with the Army, Kohler returned to academic work in the fall of 1919.

When overtaken by death in his seventy-second year, Kohler was pursuing with full vigor and with a gay heart his many activities as investigator, teacher, and administrator. His mental vigor and his enthusiasm were maintained undiminished to the day when he unknowingly closed the door on his laboratory and treasure room of chemicals for the last time. After a very brief illness, he died on May 25, 1938.

As for honors and distinctions, it is perhaps fair to say that Kohler was offered about all the honors that his friends ventured to think that he might accept. These were not numerous, and they very definitely did not include any awards associated with the delivery of an address, for Kohler assiduously declined any and all invitations to speak in public. It is not easy to say just why he adopted this iron-clad policy, and why he carefully avoided all public and social functions and all society meetings. He did feel that there is often some lost motion in such functions, and he doubtless was influenced by an unfortunate experience at the beginning of his career. After making a special trip to a meeting of the American Association for the Advancement of Science for the sole purpose of hearing a paper in his field, he was thoroughly disgusted when, through entirely unnecessary delays, the paper was crowded off the program and given only by title. On the other hand, he never expressed any criticism of the objectives of scientific gatherings and he did not hesitate to encourage his colleagues to accept speaking invitations. In the writer's opinion Kohler felt that this sort of thing was perfectly all right for those who liked it, but decided that it simply was not to his own particular taste. He had many interests of his own and many demands on his time to which he could honestly respond, and he felt under no compulsion to spend his energies on activities foreign to his inborn ways of life. This decision settled the matter, for once Kohler had set his mind on a course of action which he believed to be right he would steer to that course without any regard for what might be said or thought about it. He also had the remarkable faculty of being able to dismiss the entire subject from his mind until the time was ripe for further action. No matter how serious the problem or what personal considerations were at stake, Kohler did what was necessary and then refused to worry. Probably this quality in the man is attributable to a carefully controlled and objective intelligence whereby he was able to conserve his strength for the most worthwhile efforts. He was not at all averse to putting up a stiff fight for any cause which seemed to him just, although there was so much of both the artist and the practical strategist about him that he would not waste his energies unless the prospects of success looked reasonably bright.

Kohler was elected Fellow of the American Academy of Arts and Sciences in 1914, and Fellow of the National Academy in 1920. He served as Associate Editor of the Journal of the American Chemical Society from January 1931 until the time of his death. Perhaps one of the most significant distinctions of a life of abundant service was his informally recognized position as one of the foremost authorities on chemistry of his day and as a dominant advisor on academic appointments. With a wide-spread reputation for sagacity and keen judgment, he was consulted on all sides and exercised a profound influence on the advancement of the science.

The particular highlights of Kohler's personality which so endeared him to a legion of students and other friends are difficult to describe to those who did not know him, and to those who did any attempted description is entirely inadequate. He had an abundant fund of humor, but it was of a special brand not easily characterized, he was thoughtful and kind, and yet this often would come out in most unusual ways, and his expressions and mannerisms were so uniquely Kohlerian as to defy classification. Suffice it to say that here was a remarkably gifted scientist and teacher of modest disposition and high ideals, who could bring out the very best in those with whom he came in contact, and who was loved for a rich, colorful, and warmly human personality which delighted the hearts of his friends.

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WALDEMAR LINDGREN (1860–1939)

Fellow in Class II, Section 1, 1912

Waldemar Lindgren is most widely known for his numerous stimulating writings on the processes of ore deposition, his comprehensive philosophy of mineral genesis.

He was born at Kalmar, Sweden, February 14, 1860, and there received his early education. At the age of eighteen he entered the Royal Mining Academy at Freiberg, Germany, at that time the acknowledged leader in the world in the realm of mining, metallurgy and geology. He received his degree of Mining Engineer in 1882, and spent the next year in graduate work in metallurgy and chemistry. In June, 1883, he sailed for America with letters of introduction which procured him a position in the Survey department of the Northern Pacific Railway, then building, and the next year (1884) he became a member of the United States Geological Survey. Here, in the greatest geological organization in the world, he remained until he resigned in 1912. In 1908 he became Chief of the Division of Metalliferous Geology and in 1911 was appointed Chief Geologist of the Survey.

In 1908 the Massachusetts Institute of Technology invited him to give a series of lectures on ore deposits. These were received with such enthusiasm that he returned each year until he was finally persuaded in 1912 to become the William Barton Rogers Professor of Geology and Head of the Department of Geology at the Institute. The lectures given here, the digested results of many years of detailed field work in many parts of the world, found expression in his text, Mineral Deposits, in 1913. Successive editions appeared in 1919, 1928 and 1933. All of these reflect his familiarity with the literature of the world, his personal acquaintance with many regions and his deep understanding of nature's processes. From the appearance of the first edition to the present, his work has been recognized as a textbook and work of reference of first rank in its field.

He published almost 200 research papers and upwards of 2000 abstracts, the latter mostly in the Annotated Bibliography. He was leader of the group who in 1905 established the Journal of Economic Geology. This has now the widest circulation of any geological magazine in the world. He remained throughout his life one of its Associate Editors.

During 1927–28, while chairman of the Division of Geology and Geography of the National Research Council, he was largely responsible for the establishment and financing of the Annotated Bibliography of Economic Geology. He remained in charge of this through 1938, supervising the abstracting of the enormous volume of current literature in all phases of economic geology which appeared annually in all the languages of the world. His thorough knowledge of many languages rendered him peculiarly fitted for this position.

Dr. W. H. Newhouse, his successor at the Institute, says of him, "For decades Lindgren has been recognized as the world's leading student and interpreter of ore deposits. He made important contributions to our knowledge and theory of alterations or changes in the rocks adjacent to fissure veins and igneous intrusions; the process of replacement; the influence of physical conditions on redeposition; the role of igneous processes in the formation of ores; the conception of ore deposition within certain geological periods and provinces; and the importance of colloids in the formation of certain ore deposits."

He was a member of numerous American and foreign societies and past-president of several of the American ones. Amongst the many other honors he received was the Wollaston Medal of the Geological Society of London.

In 1886 Waldemar Lindgren married Miss Ottolina Allstrin of Gothenburg, Sweden, a charming, sympathetic woman and true companion until her death in 1929. He died on November 3, 1939, after an illness of eleven months. Up to his illness he had been in his office at the Institute nearly every day, at work on his research problems, writing and talking with the students and teachers.

Doctor Lindgren was a stimulating teacher and he drew students from many lands. These rapidly became his friends with whom, after leaving school, he kept in helpful touch. In disposition he was kindly and retiring, with a ready joke and smile.

Hervey W. Shimer

JACOB GOODALE LIPMAN (1874-1939)

Fellow in Class II, Section 2, 1921

The death on April 19, 1939 of Jacob Goodale Lipman brought to its end the truly extraordinary career of an active, gifted, humane man. Born in Friedrichstadt, Russia, on November 18, 1874, he immigrated with his family to New York in 1888. After a few years in New York City the family moved to a farm in Woodbine, New Jersey and his work on the farm and attendance at the Baron De Hirsch Agricultural School in Woodbine initiated Lipman's lifelong interest in agriculture. His career as a student in the New Jersey State College of Agriculture at Rutgers University (1894-98) and as a candidate for the master's and doctorate degrees at Cornell University (1900-03) was uniformly brilliant, and its promise was realized upon his return to Rutgers in his steady ascent to the Professorship of Agriculture (1913) and the Directorship of the New Jersey Agricultural Experiment Station (1911). During this period Lipman conducted major investigations in soil chemistry and bacteriology that eventuated in his classical book, Bacteria in Relation to Country Life (1908). In addition, during this period he went as lecturer to the Universities of Illinois and Cornell (1906), Tennessee (1909, 1910), Iowa (State College, 1910), Nebraska (1911) and later to Columbia (1920). His remarkable experimental work on the role of soil bacteria in plant nutrition, on nitrogen utilization by plants, on the soil chemistry of sulphur, phosphorus, selenium and other elements led to the award to him as a "great captain among scientific investigators" in 1934 of the Chandler Medal of Columbia University.

Lipman was not only a brilliant investigator in his own right. He encouraged and promoted the activities of a long line of able students whose manifold contributions to scientific agriculture have been internationally applied. As Corresponding Member of various foreign agriculture academies, as editor-in-chief of Soil Science and as editor of other agricultural journals and books, he propagated extensively and continuously the facts and theories of soil science. His assiduous promotion of scientific agriculture was conducted through membership in the leading agricultural societies of the world and by his attendance at numerous international conferences, culminating in his presidency of the first International Soil Congress in 1927.

Lipman's eminence in his field was early recognized by his election to this Academy in 1921. Thereafter honors and responsibilities multiplied. He was the official American delegate to the General Assembly of the International Institute of Agriculture in Rome (1922, 1924, 1926), delegate to various international soil conferences, to the International Nitrogen Conference (1926), the World Dairy Congress (1928), the International Chemical Technical and Chemical Congress of Agricultural Industries (1937). In 1927 Lipman was chosen by English and American philanthropists to report on the agricultural possibilities of Palestine and his judgment of its great potentialities has been amply confirmed by subsequent developments.

In addition to his work for world agriculture Lipman has served his city, his state, his nation. He was a member of the New Brunswick Board of Education and the City Planning Commission, President of the New Jersey Health and Sanitary Association, member of the New Jersey State Teachers' Association, The New Jersey State Chamber of Commerce and State Planning Board. As Director of the State Experiment

Station he developed the plant and activities to a remarkable extent. Its continuous progress has attained world-wide recognition. He served the cause of modern science as one of the testifying educators at the famous Scopes trial. In national affairs his cooperative activities with the United States Department of Agriculture have been long and fruitful. In 1933 President Roosevelt summoned him as consultant on national reforestation and in 1935 appointed him member of the National Resources Board. As director of the Jewish Agricultural Society he assisted in the development of the important back-to-the-land movement among American Jewry.

This man worked hard all his life. He shunned no responsibilities, rested not on his laurels. And throughout a life of incessant and demanding activity he remained a simple, friendly human being. He was a kindly, affectionate husband and father. To his parents, Michael Gregory and Ida Birkahn Lipman, he was always an attentive, devoted son. In ordinary converse the professor, the executive, the hard-pressed administrator gave way to the humorous, wise, democratic man. As friend and counselor to many, Lipman was invariably thoughtful and considerate. He was a wise man, an able man, a courteous man, but above all a good man.

GREGORY PINCUS

ARCHIBALD BYRON MACALLUM

(1858–1934)

Foreign Honorary Member in Class I, Section 3, 1930

Archibald Byron Macallum was born at Belmont, Ontario, in 1858. He died on April 5, 1934.

During his early years Macallum was a school teacher in a rural Ontario school and later in the high school at Cornwall, Ontario. In 1883 he became lecturer in biology at the University of Toronto, and in 1890, after physiological studies at Johns Hopkins University and medical studies in Toronto, he was appointed professor of physiology in that University. He retained this post until 1908 and was then elected to the newly founded chair of biochemistry in the same University. This post he held until 1916. In 1917 Macallum became the first chairman of the Canadian National Research Council and in large measure guided the new body in the troubled times of the War. From 1920 until 1928 he was professor of biochemistry in McGill University. He was president of the Royal Canadian Institute from 1895 to 1898, Herter lecturer in New York in 1918, Hatfield lecturer in Philadelphia in 1917, visiting professor at the Peking Union Medical College in 1921. He received honorary degrees from Aberdeen, McGill, Yale, Dublin, and Toronto and was a fellow of the Royal Society of London, the Royal Society of Canada, and a member of the American Philosophical Society and the Association of American Physicians. Macallum was elected to this Academy in 1930.

The influence of Professor Macallum upon teaching and science in Canada was strong and enduring. In the field of general physiology he was perhaps the first Canadian pioneer. His investigations included studies of the distribution of iron, phosphorus, potassium, calcium, and chlorine in cells and tissues and led him to the development of methods of micro-chemical analysis. He was especially interested in the distribution of potassium in plant and animal cells and in the interpretation of his results in their relations to surface tension. He also studied the relation of surface tension to muscular contraction.

For many years Macallum was interested in the relations between sea water and the body fluids and tissues of animals and the bearing of the facts that he carefully assembled on the evolution of marine organisms. Observing that the blood of marine invertebrates resembles sea water as it is found today, while the body fluids of vertebrates differ widely in respect of their inorganic constituents, he suggested the hypothesis that the present composition of the fluids of vertebrates corresponds to that of sea water of the Cambrian or Silurian ocean.

This study, for which he is best known, is a sign of his interest in the broad problems of biology. His breadth of interest, his wide learning, his shrewd judgment, and his effective teaching have greatly influenced Canadian science and seem destined to continue to exert an influence.

LAWRENCE J. HENDERSON

WILLIAM McDOUGALL (1871–1938)

Fellow in Class IV, Section 1, 1922

William McDougall, who died at Durham, North Carolina, November 28, 1938, began his professional career as a research worker in anthropology. He ended it pre-eminent as a psychologist. So intense was his interest in psychology that no one, in this or any earlier time, surpassed McDougall in effort to contribute to the progress, not only of general psychology, but of abnormal psychology and social psychology as well. That he did contribute notably is the consensus even of those provoked to vigorous dissent by some of the principles and views on which he was most insistent.

It might not inaccurately be added that William McDougall had dedicated himself to the scholar's life from boyhood. He was born in Lancashire in 1871, of Highlands Scottish ancestry on his father's side, of English on his mother's. To the fact that he was of a first generation of crossbreds he attributed the individualism, the aloofness, and the critical skepticism which always characterized him, but which did not mask from those who came to know him well the essential fineness and kindliness of his nature.

A precocious child, McDougall, at five entered a boys' school, where for some years he was the youngest but perhaps the brightest pupil. He was only fifteen when, after a year of study at Weimar, he entered the University of Manchester, where he specialized in biology. From Manchester, at nineteen, he moved to Cambridge University, gaining a scholarship in St. John's College and entering as a medical student. He did this with no idea of practicing medicine, but rather because medical studies seemed to him peculiarly desirable "to one who aspires to work in any of the sciences concerned with man."

At Cambridge, and later at St. Thomas' Hospital in London, McDougall worked in many such sciences, his courses including physiology, anthropology, anatomy, pathology, bacteriology, neurology, medicine, and surgery. He had been graduated from Cambridge with the highest honors, and, on completing his studies in London, won a fellowship in St. John's College. Many years later, within a few days of his death, he was elected an honorary fellow of this same Cambridge college in which he had so distinguished himself as an undergraduate.

His hospital days done, McDougall had to make definite choice of an occupation. He had already decided that his must be an occupation giving him opportunity to gain greater insight into the mysteries of human nature. Such an opportunity seemed to be afforded by an invitation to join the Cambridge Anthropological Expedition to Torres Strait. Five months only McDougall spent in the islands of Torres Strait, then went to Borneo to assist Dr. Charles Hose in studying the head hunters. A belated product of these studies was his publication, with Hose, in 1912, of the two-volume work, *The Pagan Tribes of Borneo*, a survey of all aspects of the lives of these peoples. It was in this same year, 1912, that McDougall was elected a fellow of the Royal Academy, thus realizing an ambition of his youthful years as a Manchester student.

But this was some twelve years after his return from Borneo to Cambridge. On returning, McDougall dallied with the thought of making field anthropology his chief endeavor. Largely as a result of reading William James' *Principles of Psychology,* he put aside this idea in favor of laboratory psychology, and began study under G. E. Müller at Göttingen, where he resumed experiments, begun at Cambridge, in the field of color vision. Soon afterwards McDougall himself became a teacher of laboratory psychology at University College, London. From London, in 1904, he went to Oxford as a reader in mental philosophy, a post which he retained to 1920 and one which gave him opportunity to teach psychology in a far broader way than at University College.

His *Physiological Psychology* was published in 1905. Three years later there appeared his *Introduction to Social Psychology,* with its forthright challenge to the mechanists by its emphasis on instinct and purpose, and its demand for an acceptance of psychic causation. Received in many quarters with enthusiasm as being the first serious attempt to make psychology of service to the social sciences, criticism of its basic theory soon was heard. McDougall, far from yielding ground, gave his critics fresh cause for complaint with his *Body and Mind* (1911) to which he defiantly added the subtitle, *A History and Defense of Animism.* Souls might be out of fashion, as William James had said. McDougall for his part felt that a soulless psychology needed radical revision to accord with the facts of human life and to become practically helpful to mankind.

Henceforth, accordingly, he devoted himself mainly to the task of reinforcing the principles and elaborating the views first stated in his *Social Psychology*. This task was interrupted by the World War, in which McDougall served, first as a private in the French army, then as an officer in the English army in charge of a hospital for victims of shell shock. The war ended, he wrote his *Group Mind*. This appeared in 1920, the year McDougall accepted an invitation to teach at Harvard University. Various motives influenced his acceptance, perhaps not least being the fact that at Harvard he would be a successor to William James. For James was one of the only two psychologists, Stout being the other, of whom McDougal felt himself to be "in some degree the disciple and humble pupil."

He came to America to find that not only the soul but Jamesian psychology itself was somewhat out of fashion, with behaviorism rampantly the mode. Unperturbed, McDougall again hoisted the banners of instinct, purpose, and psychic causation, not only with papers and addresses, but with his books, *Outline of Psychology* (1923) and *Outline of Abnormal Psychology* (1926).

The controversy thus aggravated was not lessened by the interest McDougall displayed in psychical research, a field of inquiry disdained by most psychologists. There was no denying, however, that he had forced psychologists to consider important problems commonly ignored, and no denying his power both as a systematist and as a controversialist. For all the dispute about his findings, McDougall has recorded that he was happy in his new environment. Certainly he did not lack friends, among these being Morton Prince, of whose *Journal of Abnormal Psychology* McDougall had been an associate editor since 1913. It was at his suggestion that Prince broadened the range of the *Journal* to take in social as well as abnormal psychology.

McDougall remained at Harvard until 1927, then became head of the department of psychology at Duke University in Durham, North Carolina. At Duke he continued in his dual role of teacher and productive scholar. *Janus—the Conquest of War, Character and the Conduct of Life, Modern Materialism and Emergent Evolution, World Chaos—the Responsibility of Science, The Energies of Men, Religion and the Sciences of Life, The Frontiers of Psychology, Psychoanalysis and Social Psychology*, and *The Riddle of Life* are the titles of McDougall's books published during his tenure at Duke University. To the end—*The Riddle of Life* was published shortly before he passed away—McDougall maintained his struggle against mechanism. To the end he fought for psychic causation and his purposive or hormic psychology, a psychology "which asserts that active striving towards a goal is a fundamental category of psychology, and is a process of a type that cannot be mechanistically explained or resolved into mechanistic sequences."

Few scientists of equal eminence have been so prolific in authorship. Recently May Smith, of the London School of Hygiene, has issued a bibliography of McDougall's writings and this extends to 150 items. Of his works the most influential probably has been his *Introduction to Social Psychology*, the twenty-third edition of which, a revised and enlarged edition, appeared in 1936. His *Outline of Psychology* and *Outline of Abnormal Psychology* form with the *Social Psychology* a trilogy which deserves to be designated as William McDougall's *magnum opus*.

At Duke University, moreover, McDougall by no means gave all his working time to teaching, reading, and writing. Much time he gave to an unusual series of experiments begun at Harvard and terminated only by his death seventeen years later. This was a series of experiments with white rats, having as its purpose a testing of the Lamarckian theory of the inheritance of acquired characteristics.

As far back as his Cambridge days McDougall had rebelled against the prevailing rejection of Lamarck's theory. The theory, he held, had never been put to the test of experiment; its rejection "was purely a deduction from the mechanistic dogma in biology." Finding at Harvard University a small laboratory for animal psychology, McDougall resolved to test the Lamarckian theory himself. At his death the experiments thus initiated had been carried through fifty generations of white rats, and four detailed reports had been published in the *British Journal of Psychology*. Varied most ingeniously, these experiments gradually brought to McDougall the belief that he had demonstrated at least some degree of Lamarckian inheritance. His son, Kenneth, who had long assisted him in this research, continues the experiments.

If these Lamarckian tests constituted one of

McDougall's two avocations, the other was psychical research. His interest in psychical research flowed logically from his craving to master the secrets of human nature, and from his characteristic impatience with dogmatic scientific negation. "It seemed to me a scandal that psychologists should refuse to lend a hand or at least moral support" to organized study of occult phenomena. William James, of course, had been of a like mind, and had actively engaged in psychical research. McDougall went even further than James.

As the latter had done, he accepted election to the presidency of the Society for Psychical Research, the parent English society, which he had joined in 1901. On settling in America he became president of the American Society for Psychical Research; and, in 1925, was to the fore in the founding and organizing of the Boston Society for Psychic Research, remaining on its council to his death. More than this, finding at Harvard University an unused fund for psychical research, McDougall sponsored the first investigation of telepathy at an American university. And later, at Duke University, he specifically introduced psychical research into that institution's field of studies, opening the psychological laboratory to J. B. Rhine and his associates for their experiments in what Rhine has termed extra-sensory perception.

Both of these avocations, the Lamarckian experiments and psychical research, were of course directly linked with McDougall's vocation. It has been truly said of him that he was thinking psychology all the time. Aside from psychology, his one great interest was in his home life. In 1899 he married Miss Anne A. Hickmore, of Brighton, England, and they had five children, Lesley (now Mrs. Paul Brown) Duncan Shimwell, Angus Dougal, Kenneth Dougal, and Janet Aline. In the short autobiography he wrote for Murchison's *History of Psychology in Autobiography*, McDougall paid a beautifully phrased tribute to his wife's helpful influence upon him and to the joy his home life had brought him.

In that same autobiography, on the other hand, he wrote pessimistically of the outcome of his efforts to help man to greater knowledge of himself. His pessimistic doubts were far from being warranted. Since their expression, nearly ten years ago, there has been growing appreciation of the worth of his contributions. One would seem safe in predicting for William McDougall and his purposive psychology a lastingly important place in the history of psychology.

H. ADDINGTON BRUCE

GEORGE BURGESS MAGRATH (1870–1938)

Fellow in Class II, Section 4, 1933

George Burgess Magrath was born in Jackson, Michigan, on October 2nd, 1870. His father was the Reverend John Thomas Magrath; his mother was Sarah Jane (Herrick) Magrath. The father in his work moved from place to place, so that in the first twelve years of his life George was resident in succession in Jackson and Battle Creek, Michigan, a suburb of Philadelphia and finally a suburb of Boston. In the latter, Hyde Park, and later in Mattapan, George showed an early ability in music, later serving as organist in his father's church, the Church of the Holy Spirit in Mattapan. In later years this interest in music continued, and he participated in the activities of the Cecilia Society, the Handel and Hayden Society, the Harvard Alumni Chorus and the Sängerfest, besides being a regular attendant at the concerts of the Boston Symphony Orchestra, throughout his life.

Three years in Hyde Park High School, one in the Roxbury Latin School, graduating at the head of his class, four years at Harvard College with A.B. magna cum laude in 1894, four years in the Harvard Medical School with M.D. cum laude (the highest honor from that school at that date) in 1898 and a Harvard A.M. in 1899, gives the story of his formal education.

From his graduation to his death Dr. Magrath was a member of the teaching staff of the Harvard Medical School as follows.

1898–1900	Assistant in Pathology
1900–1901	Austin Teaching Fellow in Pathology
1901–1905	Assistant in Pathology
1905–1909	Assistant in Hygiene
1907–1931	Instructor in Legal Medicine
1931–1937	Professor of Legal Medicine
After Sept. 1, 1937	Professor Emeritus

Dr. Magrath was a very excellent teacher. In his earlier days in pathology his demonstrations were popular with students. He was enthusiastic, systematic and clear in didactic teaching, a quality which became even more evident in his lectures later on, when he was giving instruction in legal medicine. These he aptly, often dramatically, illustrated from his personal experience in a way to make remembered the facts he was bringing to his class.

Trained under Councilman and Mallory and with practical experience at the Long Island, the Carney, the Cambridge, the Faulkner and St. Elizabeth's hospitals, Dr. Magrath became an excellent pathologist. His technique in the performance of an autopsy was masterly, and his keen observation recorded many details, some of which might, and often did, prove of the greatest importance in fixing the responsibility for a crime of violence. In his earlier work, when he was assistant to the secretary of the Massachusetts Board of Health, he began to show qualities, which made so successful his long years in the office of Medical Examiner. He was set to study the adulteration of sausages. Treating these as a body tissue, he hardened, embedded, sectioned and stained. The paucity of striated muscle fibers and the excess of starch granules, which he identified as corn meal, were convincing evidence of the richness of the adulteration of the original sausage.

In 1907 Governor Curtis Guild appointed Dr. Magrath Medical Examiner of the Northern District of Boston, an office which had been created in 1877 and for thirty years had been held by Dr. F. A. Harris. For the next twenty-eight years Dr. Magrath competently filled that position. In this office Dr. Magrath rapidly became recognized as a leading expert in New England in the solution of the problems of crime by violence. His fine basic training in pathology, his skill and exactness in post-mortem examinations, his logical processes of thought and exposition, his intellectual independence, his unquestioned honesty and courage, made of him an expert in court and out, whose opinions carried the greatest weight. To be cross-examined was a challenge to his knowledge and intellectual acumen which he enjoyed; rarely could he be caught unawares by opposing legal talent. More and more were his advice and his opinions sought beyond the bounds of his own district; more and more was his help asked by others in similar offices, so that his influence in legal medicine steadily increased. When New York City was planning changes in its plan of legal medical work, Dr. Magrath was an important advisor.

During Dr. Magrath's twenty-eight years as Medical Examiner he established many important procedures and made precedents, which now largely have become recognized as determining factors of the work of Medical Examiners in relation to Legal Medicine. In this way and by his own individual work Dr. Magrath had an important part in the development here of legal medicine into a science and art deserving of recognition as a significant department of medicine, a development which, started by Dr. Magrath and furthered by the generosity of Mrs. Lee, may be expected to expand and progress under succeeding professors of legal medicine until Harvard will have an actual Institute, in which all phases of the many sided problems of Legal Medicine can be investigated, taught and practiced.

In person Dr. Magrath was a picturesque figure, about which gathered many legends. He was erect and broad chested; with shoulders thrown back and chest forward he created the atmosphere of great physical strength, which in fact he had, as exemplified by his prowess as an oarsman, he for many years appearing, not alone on the Charles for recreation but in crews in various races, often winning both on the Charles and Schuylkill Rivers. His mane of hair, first red, then graying, eventually white, towered over a broad brow and finely chiselled features. These with his habitually worn flowing Windsor tie gave him the appearance of musician or artist rather than medical man. Dr. Magrath was genial, enjoyed social intercourse and was much beloved by a wide circle of friends. Under the exterior that might seem brusque there lurked gentleness and a great sympathetic kindliness, often commented upon by those with whom Dr. Magrath came into contact by reasons of the requirements of his office of medical examiner; what had seemed in advance an ordeal to be faced turned out often to be no ordeal at all on account of these qualities of Dr. Magrath.

Besides membership in the Academy from May 10, 1933, Dr. Magrath had the following organizational activities; Major, Massachusetts

State Guard, World War; Member, American Medical Association, Massachusetts Medical Society, Massachusetts Medico-Legal Society, New England Amateur Rowing Association (pres. 1899–1932), National Association of Amateur Oarsmen (vice-pres. 1928–); Member, Rowing Com. of Olympic Games, 1932; Member, Phi Beta Kappa (hon. 1934), St. Botolph Club, Union Boat Club (Boston), Penn Athletic Club (Philadelphia), Players Club (New York). By nature he was clubable, friendly, a fine companion, loved by many in all walks of life, notably by his fellow members in the St. Botolph Club where, never having married, much of his life centered.

Dr. Magrath died on December 11, 1938, after a brief illness, respected by the Commonwealth of Massachusetts and by Harvard University, both of which he had served so well for so long, and loved by a very large circle of devoted friends, lay and medical.

Henry A. Christian

WILLIAM JAMES MAYO (1861–1939)

Fellow in Class II, Section 4, 1921

Minnesota born, a small town product, for Le Sueur, where he was born, still has less than 2000 inhabitants, William James Mayo in cooperation with his brother, Charles Horace Mayo, made of another Minnesota small town, Rochester, a world known medical center of surpassing efficiency and effectiveness. Why? Because there they utilized modern means for medical diagnosis and surgical practice to give to their patients a conscientiously thorough diagnostic study and a surgical technique perfected by diligent practice, increasingly so as more and more patients sought in Rochester a surcease from suffering in the skillful manipulation of the scalpel and a highly perfected post-operative care. Thought of usually as being a surgical clinic, in its many years of existence more patients have received non-operative than operative therapy at the Mayo Clinic.

After graduation from the Medical School of the University of Michigan in 1883 William James Mayo began at once the practice of medicine in Rochester, Minnesota, with his father, to be joined there in 1888 by brother "Charlie." In this small town the Sisters of Charity had a hospital, St. Mary's, and here began that surgical work that later on was to have international acclaim, and always St. Mary's has been the center about which revolved the growing activities and enlarging housing of the Mayo Clinic.

"Doctor Will," as he was known to junior associates and well nigh countless patients, had the genius of foresight and the wisdom to see that there was a place in the world for a highly organized professional care of the sick combined with the teaching of doctors young and old and the investigation of disease. Altruistically to this end into the Mayo Clinic went a very considerable portion of the profits, for neither he nor his brother cared for great riches. Believing that the Mayo Clinic could and should play a large role in American medicine for all time and that universities above all other institutions possessed the probability of permanence, he and his brother presented to the University of Minnesota more than two and a half million dollars to endow the Mayo Clinic as a post-graduate school of its School of Medicine. Thus the Mayo Foundation of the University of Minnesota has come into existence to carry on the cordial spirit of "Doctor Will" and "Brother Charlie" in freely showing to all comers what had been learned at the Mayo Clinic.

Of the Mayo Clinic recently Harvey Cushing (Science, Sept. 8, 1939) wrote as follows: "It was, to be sure, a Catholic foundation in which Sisters of Mercy doubtless prayed for the recovery of their patients. But it was not primarily for prayer, however efficacious, that the afflicted as by a magnet came to be drawn to that particular shrine. It was rather the world-wide reputation of two forward-looking men whom I like to remember as they were thirty years and more ago, young and vigorous; each blessed with rare surgical judgment, each with hands which seemed possessed, in an emergency, with an uncanny ability to do, unflustered, just the right thing at the right moment. At this shrine there was plenty of ritual, to be sure, but it was the ritual of the well-drilled, silent, operating room, where for every movement there is a reason; where the incense in the air is not to conceal corruption but to produce painless sleep; where the water in which gloved fingers are dipped is holy only because it is sterile."

William James Mayo was tall, handsome, inspiring looking, breathing forth a simple cordiality to patients and strange doctors. Quietly, unassumingly in clinic and operating room he showed and told of his surgery; anywhere he would be looked upon as a great personality; he had a fine and wide influence on the progress of medicine and surgery here and throughout the world. Little surprise is it that widely he was honored as well did he deserve. F.R.C.S., Edinburgh, '05, England, '13, Ireland, '21; F.R.S.M., England, '26; LL.D., Toronto, '06, Maryland, '07, Pennsylvania, '12, McGill, '23, Pittsburgh, '24, Carleton College, '28, Manchester, '29, Temple University, '30, Aberdeen, '33, Minnesota, '35, Notre Dame, '36, Villanova, '37; Sc.D., Michigan, '08, Columbia, '10, Leeds, '23, Harvard, '24, Marquette, '29, Northwestern, '29, Yankton, '37; M.D. in Surgery, University of Dublin, '23, University of Havana, '29; Col. M.C., U. S. A., Brig. Gen., M.O.R.C.; D.S.M. (U. S.); Gold Medal, Nat. Inst. Soc. Sc., 1919; Henry Jacob Bigelow Gold Medal, Boston Surg. Soc., 1921; Com. Royal Order North. Star (Sweden) '27; Finlay D.S.M. (Cuba) '29; Cross of Roy. Order, Knight Com. of Crown of Italy, '32; commemorative plaque of the American Legion presented in person by President of U. S. A., '34; President Am. Med. Assoc., 1906–07; member Nat. Acad. of Sciences; member Am. Acad. of Arts and Sciences; member of many other national and foreign societies.

William James Mayo died July 28, 1939 at the age of 78 only a few months after the death of his brother Charles with whom there had been the closest and most devoted association throughout all the years of their constructively useful lives.

Henry A. Christian

CHARLES LADD NORTON (1870–1939)

Fellow in Class I, Section 2, 1907

Charles Ladd Norton was born in Springfield, Massachusetts, December 11, 1870. His father, Francis Norton, was Treasurer of the city of Springfield but as an avocation was interested in making jewelry, becoming a skilled craftsman in the art. It was in helping his father in metal working that Norton began to develop the unusual manual skill that was characteristic of him throughout his life. Only a few months before his death he was actively engaged in the development of a machine for the manufacture of synthetic textile fibre, doing much of the delicate instrumental work with his own hands.

Although his family had hoped that he would become a minister, his interest in mechanics and electricity was compelling and, after his graduation from high school and a period of service as clerk in his father's office, he went to Technology, graduating in 1893 in the Department of Electrical Engineering. His only job as electrical engineer was during a short period of employment with the Boston Edison Company. In the Fall, after his graduation, he returned to Technology as Assistant in Physics under Silas Holman. He advanced through the grades, finally becoming Head of the Physics Department.

Shortly after Roentgen's discovery of the X-ray, Dr. Francis Williams of the Boston City Hospital realized its potential importance in surgical diagnosis. Norton, with Professors Cross and R. R. Lawrence, became associated with Dr. Williams in the development of the X-ray technique, using an old Crooke's tube as the only available instrument. These men carried out their teaching assignments during the day, but at night they and their home-made equipment were transported in an ambulance to the City Hospital to spend the night taking X-ray pictures of patients from the accident ward.

In 1898 Norton met Edward Atkinson and with him started a long series of studies in Fire Prevention and was actively concerned for many years in the development of fireproof and fire-resisting materials. This led to his design of testing devices of many kinds for high temperature measurements and heat transmission and later to the establishment of the Heat Measurements Laboratory, now an important unit in Technology's instructional and research program. Coordinated with this testing work was Norton's development of asbestos board and asbestos shingles, a field in which he was a pioneer. Later he became interested in refractory materials in general and held a number of patents relating to the manufacture of asbestos wood and refractory bricks of various kinds. He was the author of numerous papers on fire prevention, temperature measurement and refractory material.

In 1930 he became Director of the Institute's

Division of Industrial Cooperation and Research, a position which he filled with distinction up to the time of his death.

In spite of his many activities and responsibilities, Norton would always find time to listen sympathetically to the problems of the younger members of the staff and his sound advice helped them over many a hard spot. His intimate knowledge of all phases of Technology's activities has made his passing a most serious loss.

Robert S. Williams

ARTHUR AMOS NOYES (1866–1936)

Fellow in Class I, Section 3, 1899

I have often thought how much more they
need advice about life than about chemistry.

At Pasadena, on June 3, 1936, Arthur Amos Noyes* died. With his passing the scientific world lost a chemist who, for half a century, had been preeminent in developing chemical education and chemical research in America. It is infinitely easier to chronicle his scientific achievements than to give an adequate impression of his personality and of the many ways in which his beneficent influence was exerted to deepen and broaden other lives, as well as to enlarge the scope of scientific and humanitarian work in the two great institutes with which he was associated.

Frederick G. Keyes, who succeeded Noyes as Director of the Research Laboratory of Physical Chemistry at the Massachusetts Institute of Technology, has paid a fine tribute to him:

> "Noyes was an extraordinary man. Nature, in the midst of her apparent prodigal waste, occasionally turns from her molds examples which, even while deepening our sense of the mystery of her purposes, sustain our faith. He was of that rare mold: a civilized man in a world whose soul is largely barbaric. Of envy, hate, hypocrisy, arrogance, lust for place and power,—there was not a discoverable trace in his composition."

Arthur Noyes was descended from Nicholas Noyes, who, in 1663, sailed from England with a little band of venturesome pioneers to settle in America. The town of Newbury, at the mouth of the Merrimac River, was founded by them, but it was the harbor-site of Newburyport where, after eight generations, Arthur Amos Noyes was born, September 13, 1866.

His father, Amos Noyes, an able lawyer of the Essex County Bar, was a scholar well versed in legal and historical lore, facile of expression in speech and writing. Although thirty-five years older than his son, he brought zest and keen judgment to the task of educating the boy, whom he himself instructed in Latin, swimming, rowing, and sailing.

Noyes' mother, Anna Page Andrews, was married at the age of nineteen to a man many years her senior. Thus, she was comparatively young at her husband's death in 1896 and became a close companion to her son. Together they travelled widely, her keen interest in literature and the arts giving him, perhaps, his great delight in poetry. In after years he invariably carried with him, when away from home, a large volume of collected poems.

Noyes' first interest in science was developed by the study of physical geography and physics, but it remained for Oliver Merrill of the Newburyport High School to inspire him with a deep interest in chemistry. At this period began a life-long friendship with another embryonic chemist, Samuel P. Mulliken. These two boys, using as a guide *Steele's Fourteen Weeks of Chemistry* and equipped with crude apparatus of their own design, carried out many experiments in their private laboratories—to wit, the attic and wood-shed of their respective homes.

Upon graduating from high school Noyes, desirous of entering the Massachusetts Institute of Technology but finding himself without funds, decided to attempt the freshman work at home. This he accomplished, mastering all the subjects of the first year except drawing. He entered the sophomore class, aided by the Wheelwright scholarship established for Newburyport students. In 1886 at the age of nineteen he completed his bachelor's thesis in organic chemistry under F. M. Norton. Continuing in this field for another year, he was awarded the Master of Science degree and appointed assistant in analytical chemistry with full charge of a class numbering about forty. Two of his most promising students, Harry M. Goodwin and George E. Hale, were counted among his best friends in later life.

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* Based on two articles published in the American Contemporary Series, *Ind. Eng. Chem.*, *23*, *443* (*1931*); and in *Science*, *84*, *217* (*1936*). Other biographical memoirs have been written by R. A. Millikan in *Science*, *83*, *613* (*1936*); by A. A. Ashdown in the *Technology Review*, *38*, *420* (*1936*); by C. A. Kraus in the *Scientific Monthly*, *43*, *179* (*1936*), and by F. G. Keyes in the October 1936 number of the *Nucleus*, published by the Northeastern Section of the American Chemical Society.

Noyes, after a year of teaching, went to Leipsic to pursue graduate work in organic chemistry under Wislicenus. While in this laboratory he attended lectures by Wilhelm Ostwald in the newly created field of physical chemistry. He was quick to grasp the opportunities afforded by this rapidly growing subject, made the momentous decision to transfer to Ostwald's laboratory, and in 1890 was awarded the doctorate in chemistry. He returned to America to resume his duties at Technology, and for a decade was actively engaged in teaching analytical, organic and physical chemistry. Meanwhile he published a book in each subject: *Qualitative Analysis of Inorganic Substances* (1895); *Laboratory Experiments on the Class Reactions* and *Identification of Organic Substances* (with S. P. Mulliken, 1899); and *The General Principles of Physical Science* (1902).

The text on qualitative analysis received immediate recognition, and its wide acceptance did much to familiarize chemists of that day with the ionic theory and the laws of chemical equilibrium. The original scheme of analysis was incomplete in the sense that it provided for the separation and detection of the common elements only. Many of the omitted elements were, however, also of common occurrence in nature, and each year new uses were being found for them. Furthermore, the scheme provided no satisfactory tests for estimating, even approximately, the relative quantities of the elements qualitatively detected.

Foreseeing future needs, Noyes initiated an extensive research project to devise a complete scheme of analysis which would include the so-called rare elements and put qualitative analysis on a semi-quantitative basis. This marked the beginning of a long series of investigations carried out with the help of W. C. Bray and many other skillful collaborators. These investigations were published from time to time as the work progressed. There was finally published with Bray, after a quarter century of effort, a monumental treatise of five hundred pages. Noyes himself regarded this as his most important contribution to chemistry.

The second book marked the conception of a bold plan to systematize the complexities of knowledge of the empirical properties of organic compounds. This extremely important systemization was subsequently developed by Mulliken, but Noyes always retained a deep interest in it.

The third book marked the first step in the development of a course of study which embodied the ideals of Noyes in regard to teaching. It was my privilege, from 1905, to aid in the development of this course. The book has undergone many changes and revisions. Its purpose, however,—"to give the student an intimate knowledge of the fundamental principles of chemistry and a training in logical, scientific thinking such as will enable him to attack effectively the problems arising in any one of the branches of chemistry or related sciences,"—has remained unchanged. Charles A. Kraus has truly said—"It was due to Noyes more than to any one man that the method of teaching physical chemistry in America was revolutionized. He constantly emphasized the importance of general physical principles and illustrated their use and application by the problem method."

Through his research in physical chemistry, Noyes championed the cause of the ionic theory when many chemists sought to discredit it. During the first few years of his teaching career he was largely dependent on undergraduate students to carry out the many investigations in this field which absorbed his interest. His policy was to *select* the ablest students, to *interest* them in discovery, and to *train* them in research early in their undergraduate course. His dream during this early period is made clear by the following excerpt from a letter dated November 1, 1901.

> I have made a proposition to the President (Pritchett, M.I.T.) in regard to the establishment of a Research Department. It is rather an audacious proposition to make for a person who hasn't much more property than the obligations involved in the proposition require, but I feel that the highest ambition of my life would be realized if I were in charge of such a

department, and it is a favorite sentiment of mine that:

> Those love truth best who to themselves are true,
> And what they dare to dream of, dare to do.

The President is heartily in favor of the plan, but the Executive Committee has not yet acted upon it.

The progress of the plan is indicated in a second letter dated October 12, 1902.

> All consideration of the establishment of a Research Department has been postponed till next spring when the question of moving the Institute will be settled. I have applied to the Carnegie Institution for grants for my own researches and for those of Whitney and Mulliken, and expect to hear next month whether I get them. Remsen of Johns Hopkins, Smith of Pennsylvania, and Richards of Harvard are the Chemical Committee. What the Carnegie Institution does will also have a bearing on the Research Department's establishment.

Further progress is shown by the following letter to President Pritchett,* dated January 12, 1903.

> I wish to renew, with some modification, the proposition previously made in regard to the organization of chemical research at the Institute. This proposition is as follows:
>
> I will give to the Institute each year for a period of three years, with the expectation of further continuance, the sum of $3000.00, in case the Institute will establish Research Laboratories of Physical Chemistry, which shall be independent of existing departments and under the charge of a director, assign to them adequate space, equip the laboratories (at a cost estimated at $6000); appropriate annually the sum given by me and an additional sum of equal amount for the maintenance of the laboratories and payment of research workers in them, and give recognition and standing to the latter by suitable appointments as regular members of the Institute staff.
>
> The appointment of research workers as members of the Institute staff with gradations corresponding to their experience and efficiency in research, for example, as Research Assistants, Research Associates, and Research Professors, is in my opinion essential to the success of the plan; for in order to attract good men and retain them in this work, it is essential that their position be one of some dignity and that there be some prospect of future advancement.
>
> It is desirable that the laboratories be started at the beginning of the next school year.

This letter well illustrates the practicality of Noyes in considering ways and means to insure the realization of his objectives. There is no record of how he was enabled to meet the financial obligations involved in his "audacious" proposition. It is, however, a matter of common knowledge that he and his close associate, W. R. Whitney, developed (1896–98) and put in operation (at Jamestown, N. Y.) a highly profitable process for the recovery of alcohol and ether vapors lost hitherto in the manufacture of photographic printing paper. It is almost certain that this source of income encouraged Noyes to dare to carry out his cherished project.

On February 10, 1903, the Executive Committee voted to establish the proposed Research Laboratory and made provision for it in a new building.* Noyes was appointed director and given an independent budget. The Laboratory was opened on the twentieth of September, 1903. A grant of $2000 was made during that year to Noyes by the Carnegie Institution of Washington for his own investigations. Two other gifts made to the Laboratory during the first year are worthy of note,—one of $1000 from Willis R. Whitney, and a second of $1000 from a fund founded by William E. Hale.† The Carnegie Institution continued to support the investigations of Noyes over a period of many years, 1903 to 1927. Such grants aggregated the surprisingly large sum of $154,500.

During the first years of his directorship, Noyes maintained the same intimacy with the laboratory group which he had previously maintained with his individual research students. This intercourse was considerably furthered by his purchase of a sizable, seaworthy yawl. During the summer selected groups from the Laboratory were invited to explore the myriad bays and inlets of the Maine coast from Portland to Eastport. Sailing into Bar Harbor with the signal of distress flying was only one of many incidents which furnished abundant material for good-natured chaff at winter reunions.

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* The first two letters were addressed to the author while pursuing graduate work in Germany.

* Owing to the prospect of a new site, this building was hastily erected as a temporary structure. It was, however, carefully planned to suit the needs of the Laboratory.

† Father of George E. Hale.

It was on these cruises that Noyes' real personality, so effectively hidden from the outside world, was unfolded. His associates learned of his almost passionate fondness for poetry, which he would recite with intonation never to be forgotten. This fondness sometimes found expression on unexpected occasions. Once in the class-room, for example, the students were startled to hear him read, in place of the usual lecture in physical chemistry, Kipling's compelling poem, *The Explorer*. They quickly grasped nevertheless that it symbolized,—the urge, the struggle, the reward of research,—and after the first moments of incredulity, listened with rapt attention to the inspiring lines:

Till a voice, as bad as conscience, rang interminable changes
On one everlasting Whisper day and night repeated—So:
Something hidden. Go and find it. Go and look behind the Ranges—
Something lost behind the Ranges. Lost and waiting for you. Go!

As members of the crew the research associates discovered that Noyes habitually started work at four in the morning and ended at eight in the evening; and they began to understand that "infinite capacity for taking pains," which was the key-note of his success. But more than all that, they began to catch the spirit of this gentle, retiring man, albeit a born leader, and, in their own various ways, to profit by it.

This intangible spirit of Noyes permeated the whole laboratory and is evidenced by the extraordinarily large number of men—latterly leaders of science in America—who came in contact with him at an early period of their own development. By way of illustration might be mentioned W. R. Whitney, W. D. Coolidge, G. N. Lewis, W. C. Bray, H. M. Goodwin, C. S. Hudson, Yogoro Kato, C. A. Kraus, K. G. Falk, R. C. Tolman, W. D. Harkins, E. W. Washburn, R. B. Sosman, John Johnston, F. G. Keyes, and many others of this and later periods of his life.

Charles A. Kraus, who was a charter member of the research group, writes about this early period as follows:

> Noyes was an ideal director. While he kept in touch with the work of men engaged on his own problems, he nevertheless gave them complete independence in carrying out such work. In the case of others, who were working on their own problems, Noyes always exhibited helpful interest but never interfered with the individual investigator; every worker in the laboratory not only had an opportunity to solve his own problems but it was expected of him to do so. It was this impersonal point of view with regard to the problems in the Research Laboratory that contributed perhaps more than any other factor to the success of the laboratory. Yet Noyes was always interested in the men themselves and was ready to help them on every occasion.

Noyes personally contributed—for almost seventeen years—half the expense of maintenance of the Research Laboratory. During the last four years of this time he assumed concurrent control of two research laboratories, his own and the Gates Chemical Laboratory in Pasadena. In response to the call from George E. Hale across the continent, to aid in the reorganization of Throop College,* he divided his time between the two places.

The devotion of Noyes to research is shown by the fact that, despite constant physical suffering during the last few years of his life, he found time from his administrative duties to carry out during the summer months with his honors students investigations in his chosen field. Just one month before his death a comprehensive paper on *Strong Oxidizing Agents in Nitric Acid Solution* was submitted for publication. One year after his death, these students concluded and published, in a series of three papers, the final results of these investigations. These were published under his name as well as theirs, with an explanatory note in which the junior authors "assume full responsibility for imperfections and wish to acknowledge their great debt to Professor Noyes."

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* Later renamed, The California Institute of Technology.

The active participation of Noyes in the affairs of the American Chemical Society furnishes the first concrete evidence of his leadership in science. At an early date he perceived the need of a publication devoted to the review of chemical research in America. In 1895, due to his efforts, there appeared a *Review of American Chemical Research.* This was first published as a separate part of the *Technology Quarterly,* and in 1897 it was incorporated in the *Journal of the American Chemical Society,* with the explanatory note:

> This Review which has for two years appeared in the *Technology Quarterly* and as a separate publication, will hereafter be published only in the *Journal* and in the *Technology Quarterly.* Copies of the two preceding volumes may be obtained by addressing the Librarian of M. I. T.

Noyes edited this *Review* from 1895 to 1902. From 1902 to 1906* it was published by the *Journal,* only, and in 1907 it was replaced by *Chemical Abstracts.* Thus Arthur Noyes inaugurated the first review of American chemical research, the progenitor of the more general abstract journal.

Noyes also took an active part in the organization of the Northeastern Section of the American Chemical Society and became its first president in 1898. He presented to the section, over a period of seven years, five papers—two illustrated by experiments and all related to his own work or that of his Research Laboratory. In 1904 he was honored by the presidency of the parent society.

A similar record might be cited of his participation in the councils of the American Association for the Advancement of Science, and of the National Academy of Sciences. In 1927 he was elected to the presidency of the former organization. Among other honors conferred upon him were: the degree of LL.D. from the University of Maine in 1908, from Clark University in 1909, and from the University of Pittsburgh in 1915; the degree of Sc.D. from Harvard in 1909, and from Yale in 1913; the Willard D. Gibbs Medal in 1915; the Davy Medal from the Royal Society in 1927, and the Theodore W. Richards Medal in 1932.

Throughout his entire career Noyes was as much interested in scientific education, taken in its broadest sense, as he was in his own special field. From the first, he was an active member of the faculty of the Massachusetts Institute of Technology, constantly seeking ways to make more effective the principles for which he stood. He became chairman of the faculty in 1906. Technology circles were stirred, at about this time, by the proposal of a merger with Harvard. Many viewed such a step with alarm, considering it to be a definite trend away from the conception of the Institute by its founder, the great educator, William B. Rogers. At meetings of the faculty Noyes opposed the merger, and expressed his own views on education in an article published in the *Technology Review* (1905) entitled, *The Ideals of the Institute.*

Noyes was invited to become acting president of Technology in 1907, a very critical time in its history. The acceptance of this responsibility and honor entailed serious sacrifice and real hardship to one of his temperament and mode of life. Such a position necessitated constant contact with an outside world which he had hitherto purposely shunned. But he gladly accepted this important duty, and during two years he gave much thought to improving the methods of instruction, particularly for students in the first year class, and the conditions of their social life.

A keenly perceptive mind has adjudged Noyes' administration in an article which appeared in the *Technology Review* (1909). The following quotation not only outlines the accomplishments of that period, but also portrays admirably the character and personality of the man.

> In making a review of the two years' administration of Acting President Noyes, one is struck by the fact that the period has been a time, not of transition but of positive achievement and progress. Long and intimate acquaintance with the Institute and its problems made it possible for him to discern such matters as he could deal with fittingly, and to take them up without delay. This knowledge, combined with his courage and straightforwardness,

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* Under the editorship of W. A. Noyes.

has made it possible for the Institute to go forward surely and steadily.

The first essential to such advance was a better understanding between the different bodies responsible for the welfare of the Institute. It was fortunate that at the time when these bodies were acutely conscious of this need, the head of the Institute was a man who could bring to bear upon the situation his powers of truth and tact. Thanks in large measure to these powers, conditions have changed. The new day of cooperation has already begun. . . .

The thing of most significance, however, in this brief period of Institute life is the influence, not official but personal, which President Noyes has come to have. It is the result of a force of character which, in impressing itself on others, works always through candor and sympathy. "On occasions when I have talked intimately with students," he remarked in his talk on teaching,* "I have often felt how much more they need advice about *life* than about chemistry." And again, in an interview published at the time of the election of President Maclaurin, he said, referring to his own retirement: "I have no hesitation in saying that I would rather be President of the Institute than to hold any other position in the country provided I felt myself well fitted to fulfill the duties of the place. I have, however, clearly recognized that this would not be for the true interests of the Institute; for it needs at its head a man with a larger working capacity, and with certain other important qualities more highly developed."

Noyes was active in Washington during the World War, and was made chairman of the National Research Council, where he was closely associated with George E. Hale and Robert A. Millikan. At the end of the war he made the important, though reluctant, decision to give up the directorship of the Research Laboratory in Cambridge in order to devote his full time to the new California Institute of Technology.

During the years spent in California, Noyes' interest in science widened. He was devoted to Hale and the success of the 200-inch telescope. He was a member, not only of the Executive Council of the California Institute of Technology but of the Observatory Council which had direct responsibility for the telescope. In his quiet and unobtrusive way, he exerted a profound influence in all departments of the Institute. The educational policies, both graduate and undergraduate, were largely due to him. As Millikan has said,—"he spent more time than any other man on the campus trying to create here outstanding departments of physics, of mathematics, of the humanities, of geology, of biology, and of the various branches of engineering; and what these departments are today they owe, more than they themselves know, to Arthur A. Noyes."

MILES S. SHERRILL

JOHN CHARLES PHILLIPS (1876–1938)

Fellow in Class II, Section 3, 1915

John Charles Phillips was born in Boston on the 5th of November, 1876, the son of John Charles and Anna (Tucker) Phillips. He went to Milton Academy and then graduated from the Lawrence Scientific School of Harvard University with the degree of S.B., in 1889, from the Harvard Medical School in 1904, and became a House Officer at the Boston City Hospital immediately after graduation and served there for two years. He never practiced medicine professionally. On January 11, 1908, he married Eleanor Hyde of Bath, Maine, and in due season had four children—John Charles, Madelyn, Eleanor and Arthur. He is also survived by two brothers—William and George Wendell—and by two sisters—Anna and Martha P.—Mrs. Reynal Bolling and Mrs. Andrew J. Peters.

Phillips early developed an interest in travel and exploration which lasted all through his life. How many trips he made to the Canadian Rockies and through the western and northwestern portion of the United States I have no way of telling, but he camped in the Glacier National Park and named many of the prominent geographic features there long before the Park was ever thought of. I know he was in Lower California in 1910.

In 1896 he went with Peary to Greenland. Ten years later he travelled extensively in Japan and Korea with his friend Theodore Lyman.

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* An address delivered to the members of the instructing staff in March 1908.

Lyman returned and Phillips went to South China after tiger, and finally ended up in Peking. First, however, he met at Shanghai his mother and sisters and Miss Hyde and accompanied them on a trip up the Yangstse River. Miss Hyde had gone there with her friend Martha Phillips to visit William Phillips, who was at that time Secretary of the United States Legation to China. In 1907 he was in Mexico with his friend Thomas Pierce. It was on this trip that he bought and gave to the Peabody Museum the superb collection of prehistoric pottery from Casa Grande in Chihuahua. He was always doing things like this wherever he was or wherever he travelled. In 1908 he and his young wife took a long trip in a Dahabieh up the Nile, finally reaching Khartoum. In 1910 he went back to Mexico. In 1912–13 he visited the Anglo-Egyptian Sudan, especially the Blue Nile and Dinder River valleys, with Dr. Glover M. Allen, an old friend and the Curator of Mammals in the Museum of Comparative Zoology at Harvard. In 1914 he went to Mount Sinai, Arabia Petra, and up through Palestine, a long journey by camel, this time with Dr. William Mann. His last extended excursion was in 1923–24 when he travelled far and wide through Kenya, Uganda and the eastern Belgian Congo. On most of these trips he made large and important zoological collections which he gave to Harvard University. Upon these collections many scientific reports were written by several specialists. He gave the Phillips Collection of Heads and Horns, selected specimens representing nearly two hundred and fifty species with a number of world's records, to the Museum in 1929. He also gave the Museum many generous gifts of money to aid in exploration, research, and publication, and also frequently purchased important collections to add to its resources, such as the Armstrong collection of Mexican birds.

Phillips held many important positions in several institutions: He was a member of the Faculty of the Peabody Museum in Cambridge since 1931, as his father had been from 1881 until his death in 1885; and for several years President of the Board of Trustees of the Peabody Museum in Salem. He was Research Curator of Birds in the Museum of Comparative Zoology; long a Trustee of the Boston Society of Natural History; Chairman of the Massachusetts Conservation Council, and of innumerable other committees concerned with field sports, conservation, and forestry. His important services in helping to protect wild life throughout the world will be dealt with elsewhere, as well as his excellent work as "American Observer" at several important International Conservation Conferences. He was a Fellow of the American Academy of Arts and Sciences; a Fellow of the American Ornithologists' Union. He was also for six years President of the Massachusetts Fish and Game Association. He was a founder, and for seven years chairman, of the American Committee for International Wild Life Protection, and was a director of the National Association of Audubon Societies at the time of his death.

Phillips gave to the Trustees of Public Reservations several tracts of land in Boxford, Wenham and Rockport, chosen for wild life refuges and because of their natural beauty. He gave the Bolling grove of Giant Red Woods to the State of California in memory of his brother-in-law Colonel Ray Bolling, the first American officer of high rank to lose his life after America went into the World War.

Phillips joined the Second Harvard Surgical Corps in November 1915, and was commissioned an Honorary Lieutenant in the Royal Army Medical Corps and assigned to General Hospital No. 2, B. E. F. On the completion of that service he returned to this country. In September, 1917, he was commissioned a First Lieutenant in the United States Army Medical Corps, in December, 1917, was made a Captain and in May, 1918, as major he was appointed Commanding Officer of the 33rd Field Hospital of the 4th Regular Army Division. He took part in the Marne-Aisne, Saint-Mihiel and Meuse-Argonne offensives, and afterwards went to Germany with the Army of Occupation. He returned to the United States in July, 1919.

His active research began about 1909 when he was associated with Professor W. E. Castle, at the Bussey Institution, and collaborated in genetical experimentation. I vividly remember going to Jamaica Plain to watch him operate when he first transplanted the ovary of a black guinea pig into a white guinea pig. The white guinea pig thereafter produced black young and proved again the independence of the germ plasm and the soma. In 1911 and 1914 he collaborated again with Castle in two very important papers published by the Carnegie Institution of Washington on germinal transplantation and on the effects of selection in rats and guinea pigs.

His first ornithological papers appeared in 1901. In 1910 came one recording ten years of observation on the migration of water fowl at Wenham Lake. In 1912 he described a new Puma from Lower California. In this year also appeared his first paper on size inheritance in ducks. He continued for years his work on hybridization and built up an enormous collection of living wild fowl and pheasants which he used in his experiments. His published results of the breeding experiments carried on at his lovely country place at Wenham are among the most important of his many contributions to knowledge.

In 1916 he published a study of the birth rate of Harvard and Yale graduates and at about the same time he began to write concerning conservation of mammals and birds as well as further observations on the waterfowl of Wenham Lake. Then finally in 1922–26 he brought forth the great four-volume *Natural History of the Ducks,* probably the best monograph of its kind which has been done by any American naturalist and one which has been appreciated so that now it is almost impossible to obtain.

In 1928 appeared the *Sportman's Scrapbook,* to be followed by several other volumes of essays on field sports and camping which combine accurate statements of fact and great charm of expression.

Phillips was proud of his family but never spoke boastingly of his ancestors. His first forbear to graduate from Harvard was Samuel Phillips of the Class of 1650, he was directly descended, great grandson, from John Phillips, first Mayor of Boston; and two of his forebears founded Phillips Exeter and Phillips Andover Academies, and no less than eighty-five bearing the name of Phillips have graduated from Harvard College from then to the present time, not all immediate kin of course, but a great many were direct progenitors.

During the last few years he spent his winters at Severn Oaks Plantation on John's Island, South Carolina. It is interesting to note, moreover, that the first Phillips graduated from Harvard thirty years before the founding of the city of Charleston.

Last winter we made a trip together visiting the bird sanctuaries of the National Association of Audubon Societies from northern Florida to the Florida Keys and several years before that John went with me on a visit to the Harvard Botanical Garden at Soledad in Cuba and we spent some time together travelling through the island.

Of all the events of a life which has been perhaps somewhat more varied and fully occupied than the average, these two journeys stand out clearly in my mind as precious and indestructible memories.

Phillips prepared a bibliography of his published works complete from 1900 to 1932 which is to be found in the Library of the Museum of Comparative Zoology at Harvard College.

T. Barbour

R. I. P.

On a bleak November afternoon not long ago there stood with bowed head on a little knoll in the Wenham woods a cluster of heavy-hearted, sad-eyed people as a minister read the committal service and John Phillips was laid to rest. Nearby, a small brook wound its way through low bushes and the roots of scattered hardwoods. It was just the sort of cover in which a woodcock might have been most at home. The surroundings could not have been more perfect for the burial place of this beloved true New Englander.

As we turned away from the grave, we heard the sound of a shot close by. When its echo had died away many of us thought how pleased John would have been at this unconscious tribute.

H. J. C.

EDWARD SAPIR (1884–1939)

Fellow in Class IV, Section 2, 1933

Edward Sapir, who died on February 4, 1939, was one of the greatest American students of linguistics and an ethnologist of surpassing brilliance. He was also a man of rare quality.

Sapir was born in Lauenburg, Pomerania,

(January 26, 1884) and was brought to this country in childhood. He attended Columbia University (A.B., 1904; A.M. 1905; Ph.D., 1909) and was initiated into the studies of anthropology and linguistics by Franz Boas. His proficiency in the field of languages was manifested while he was still a graduate student by contributions to Indo-European philology and to Semitics. During the early period of his professional career (research assistant, University of California, 1907–1908; instructor in anthropology, University of Pennsylvania, 1909–1910) he was engaged in the analysis of a number of western Indian languages. At this time he dealt with the entire range of Uto-Aztecan tongues and published numerous significant papers and monographs.

From 1910 to 1925 Dr. Sapir was chief of the division of anthropology, Geological Survey of Canada, and, aside from his administrative duties, gave himself over to research upon the languages and cultures of various northern Indian groups, particularly the Nootka. Although his publications upon the tribes of the Northwest Coast were copious and invaluable, they represent only a fraction of the vast amount of accurate linguistic and ethnological data which he collected. The analysis of this thesaurus has been entrusted to a number of his gifted students. During his sojourn in Canada Sapir worked also upon the Sinitic connections of the extended Athapascan linguistic stock and produced lucid and penetrating papers upon the intricate social organization of the tribes of the Northwest Coast. Professor Leslie Spier, Sapir's colleague at Yale University, to whom I am indebted for the data incorporated in this sketch, informs me that Sapir's interest in the psychological implications of language and culture developed at this period of his career. If such a versatile scholar could be said to have had a paramount interest, perhaps this field represents the sharpest focus of Sapir's endeavors.

In 1925 Dr. Sapir was called to the department of anthropology of the University of Chicago and embarked upon a career of teaching which immediately established him in the forefront of the academic ranks of anthropological science. His vast knowledge, the inspirational character of his teaching, and his ability to correlate formal anthropological knowledge with the realities of contemporary life in civilized society marked him for leadership in attempts to integrate the social sciences. I think it may be said that at this period Sapir was easily the most influential figure in American anthropology. The recognition and honors which come to the scientist of outstanding ability were abundantly bestowed upon him during these years. Sapir was the cornerstone upon which that masterly organizer and teacher, Fay-Cooper Cole, rebuilt the department of anthropology at Chicago.

In 1931 Sapir became Sterling professor of anthropology and linguistics at Yale University and immediately established that institution as a center to which graduate students from all parts of the United States and from foreign countries flocked to receive his superlative instruction not only in linguistics, but in general ethnology and in the psychological and psychoanalytic connotations of language and culture. In these years Dr. Sapir contributed notably to the work of reorganization of the department of anthropology at Harvard University, which had suffered the loss of Professor Roland B. Dixon, by devoting no small part of his time and energy to the instruction of junior colleagues at Harvard who journeyed to New Haven to sit at his feet. A small incident in his career, but an important event for Harvard University, was Sapir's participation, as visiting professor, in the Tercentenary Summer School Session of 1936. In this brief sojourn many of the graduate students and instructors in Harvard University received the benefit of his wisdom and his inspiration.

This writer is incompetent to give any original and authoritative appraisal of Sapir's scientific contributions to anthropology, since they fall into areas of that vast subject which are most remote from his own specialties. It is a matter of common knowledge and of universal agreement that in the field of linguistics Sapir did not fall short of genius. His mastery of the techniques of Indo-European and Semitic philology was probably not less than his very extraordinary and even transcendent skill in primitive languages. But he was no mere grammarian and lexicographer; he brought to the study of linguistics a psychological and cultural insight which, for his students, effected the miracle of a virtual carnal resurrection of the desiccated science of philology.

Sapir's oral and literary talents were scarcely inferior to his gifts as a philologist. Not only did he understand the psychological implications of language; he could use the English language supremely well. I know this from my own experience as one of his rapt auditors. I am credibly informed by competent students of linguistics that his proficiency in the use of many other languages was equally notable, and that his ear for the reception of language was "perfect." His best known work is "Language" (1921) in which, to quote Spier, "he emphasized the more fundamental characterizations of conceptual types and degrees of synthesis. . . . Essentially, this is emphasis on language as thought rather than as form."

By-products of Sapir's scholarly work are two hundred or more titles of groups of poems, literary and musical criticisms—most of them written in the decade including his later years at Ottawa and the first part of his stay in Chicago. According to his intimate friends these are indicative of that extraordinary feeling for word and sound which were most characteristic of him as an individual and were fundamental to his interest in linguistics.

To the writer, who was not privileged to know Edward Sapir intimately, but enjoyed only the occasional contacts afforded at anthropological meetings and in the course of exchanges of brief visits, certain characteristics of the man were easily discernible. He was shy and held himself aloof from casual acquaintances until he sensed in them a genuinely friendly feeling toward him. As soon as he felt the social atmosphere sympathetic and congenial he unfolded all of his unusual personal charm and became a most brilliant and fascinating companion. His friendship and confidence once extended were enduring. There was nothing devious or calculating in Sapir. He was ready to give of his time and his intellect without thought of return or recompense. He required of the recipients of his favors only that they be honest and sincere. He manifested neither intellectual pride nor intolerance; he showed extraordinary patience and self-control under adversity.

Thus it seems to a somewhat casual colleague at a sister university that the small circle of American anthropologists has lost in Sapir not only one of its most brilliant intellects, but also a man of rare fineness of personality and of a breadth and depth of human understanding which shed lustre upon the very title "anthropologist."

E. A. Hooton

CHARLES SANFORD TERRY (1864–1936)

Foreign Honorary Member in Class IV, Section 2, 1931

Charles Sanford Terry, eminent historian and musical scholar, died November 5, 1936. The eldest son of Charles Terry and Newport Pagnell Terry, he was born in 1864. He was educated at St. Paul's Cathedral Choir School, King's College School, Lancing College and at Clare College (Cambridge) where he received the degree of B.A. in 1886 and that of M.A. in 1891. In addition the following degrees were bestowed upon Professor Terry: honorary doctor of music at Oxford and Edinburgh, doctor of laws at Durham, Glasgow and Aberdeen, and honorary Ph.D. at Leipzig University. His teaching positions were many: Lecturer in history in Durham College of Science (Newcastle-on-Tyne) at Aberdeen and Cambridge; professor of history at Aberdeen (1903–30). He was also president of the Association of Scottish History. He published many articles and books dealing with various aspects of Scottish history, as well as a "Short History of Europe" (1806–1915).

In an autobiographical sketch for "Who's Who" (England) there is a significant phrase: "hobby, music." For despite his unquestioned eminence as a teacher and writer on the history of Scotland, to the world at large Professor Terry is at once associated with a series of highly informative and charming books dealing with Johann Sebastian Bach and his time. Bach's Chorales (3 vols.) (1915–21), Bach's Original Hymn Tunes (1922), Bach: a Biography (1925), Bach's Cantata Texts, Sacred and Secular (1926), Origin of the Family of Bach Musicians (1929), Johann Christian Bach (1929), Bach's Choral and Chamber Works (1924–35), The Four Part Chorales of Bach (1929), Bach, The Historical Approach (1930), Bach's Orchestra (1932), The Music of Bach: an Introduction (1932). In a field seemingly exhausted by the researches of Spitta, Schweitzer and Parry, these volumes of Professor Terry's are astonishing for freshness of viewpoint, a scholarly thoroughness which is never pedantic and a vividness of presentation which make his volumes a delight to laymen as well as to musicians. For accurate information on Bach's music, style and environment these studies are indisputably classics. To Professor Terry the musical world must ever remain deeply indebted.

E. B. Hill

GEORGES URBAIN (1872–1938)

Foreign Honorary Member in Class I, Section 3, 1938

Georges Urbain (April 12, 1872–November 5, 1938) was Professor of General Chemistry at the Sorbonne, Director of the Institut de Chimie de Paris, and co-Director of the Institut de Biologie Physico-Chimique. He was a brilliant and a versatile man, a painter of landscapes, a sculptor and a musician of distinction, and one of those, of whom there will be very few more, who are to be credited with the discovery of a chemical element. He discovered lutecium, discovered or assisted in the discovery of celtium, and helped by his numerous researches on the rare earths toward the identification and characterization of several others. His work and his speculation on complexes constitute a fundamental contribution to inorganic chemistry and raise questions for the organic chemist which remain to be answered. His lectures at the Sorbonne attracted large and enthusiastic audiences of students. His writings, always clear and always in beautiful style, are marked by a philosophic interest in their subject, in the implications and connotations of the facts which are reported, and in their historical background.

Urbain's work in music is discussed in an article by Henry Mesmin, "Georges Urbain, Compositeur," in a commemorative volume, soon to be published, which will contain discourses pronounced on the occasion of the scientific jubilee of Georges Urbain, 1938. An article by Pierre Urbain, "Georges Urbain, Peintre et Sculpteur," will appear in the same volume. Paul Job's "Notice sur la vie et les travaux de Georges Urbain," *Bull. soc. chim.*, [V] *6*, 745–766 (May 1939) gives an excellent account of Urbain's scientific work and contains a bibliography which lists 110 scientific papers and 8 books. Other references are—Georges Champetier and Charlotte H. Boatner—"Georges Urbain," *Journal of Chemical Education*, soon to be published (1940). Paul Job—"La carrière universitaire et le jubilé scientific de M. G. Urbain," *Annales de l'Université de Paris*, *13*, No. 6, 509 (1938). Ralph Oesper—"Georges Urbain," *Journal of Chemical Education*, *15*, 210 (1938). Claude Seymart—"G. Urbain: Le Tombeau d'Aristoxène. Essai sur la musique," *La Revue Musicale*, pp. 179–180 (1924–1925).

Tenney L. Davis

ARTHUR EDWARD WELLS (1884–1939)

Fellow in Class I, Section 4, 1929

Into a life-span of less than fifty-five years Arthur Wells crowded that abundance of achievement which marks the outstanding man. Born at Saxonville, Massachusetts, on July 27, 1884, he gained through some happy inheritance a boundless vitality and a striking capacity for accomplishment, coupled with a genuineness and modesty that later successes could not modify.

It was indicative of his vigor and initiative that, upon graduation in 1906 from the Massachusetts Institute of Technology with the degree of Bachelor of Science in Mining Engineering and Metallurgy, he should immediately head for the virile West and find a position. And it was a forecast of his kinetic career that in the ensuing five years, at lead-silver smelters of the American Smelting and Refining Company at Leadville, Colorado, and at Murray, Utah, he should rise through the levels of assistant chemist, chemist, chief chemist, assistant superintendent and research metallurgist. In 1911, at the age of twenty-seven, he was appointed chief metallurgist at the company's enormous Garfield, Utah, smelter, final link in the chain of operations that draws valuable metal from a mountain of lean ore at Utah Copper, first of the famous "porphyry coppers." This responsible post he held for two years until called to a new type of service.

While at the Murray Smelter in the Salt Lake Valley, Wells had directed investigations relating to the damage which the fumes from smelting sulphide ores cause, when in sufficient concentration, both to vegetation and to animals which subsist thereon. This "smoke problem," involving a tangled intermixture of legitimate and fraudulent claims by agricultural interests against the smelting companies, had grown to great monetary importance in several regions, besides becoming a fertile ground for unscrupulous or inflammatory political activity. In 1913 the United States Bureau of Mines established the Selby Smelter Commission to investigate alleged smoke damage near San Francisco Bay. Wells was chosen as best fitted to conduct the chemical and metallurgical studies. The results, published by the Government, were chiefly his contributions; he was the first to treat the smoke problem scientifically, through accurate chemical controls and appropriate experimental procedure, and the volume remains the classic authority on this subject.

On completion of this inquiry at the end of 1914, Wells was led to join the Bureau of Mines by the opportunities there offered for broad research in the directions of particular interest to him. During his six years in that organization, he was successively metallurgist, assistant chief metallurgist and assistant supervisor of experiment stations. But during 1917–18 he was "loaned" to the Ordnance Office of the War Department and later became Associate Chief of the Acids, Sulphur and Pyrites Committee of that Board, having charge, in this connection, of the coordination of sulphuric acid production throughout the nation.

In 1920, long controversy and agitation regarding smelter smoke damage in Montana led to the establishment of the Anaconda Smelter Commission, and Wells was placed in charge of the chemical and metallurgical investigations and the preparation of the final report.

During all this work Wells sought to find technical and economic means for removal and especially for utilization of the sulphur from smelter smoke, so that this malign ingredient might be converted into a valuable and beneficent product. Artificial fertilizer seemed the most promising direction of utilization, and Wells was largely instrumental in inducing the Anaconda Company to enter the fertilizer business. He was thus brought into contact also with phosphate, potash and nitrogen resources and utilization, to all of which he made important contribution from the standpoints of science, production and marketing.

For five years from 1921, Wells was retained as consultant by important interests in New York City, including Guggenheim Brothers, J. P. Morgan & Co., Anaconda Copper Mining Company and Indian Refining Co. With marked success he executed commissions that involved such further diverse problems as the investigation of metallurgical and chemical undertakings as a basis for financing, improvement in petroleum refining, examination of the nitrate industry and of copper leaching in Chile, and plans for a cement industry in Alaska.

In 1926, Wells was invited to the chair of non-ferrous metallurgy at Harvard. With characteristic energy and thoroughness he plunged into this new phase of his calling. His instruction possessed that directness, practicality and insight which sprang from his temperament, and his students sensed his current knowledge and mastery of his field. While appreciating the attractions of academic life, Wells never felt fully at home within it. To its tempo and its repetitions he was not adjusted. He once remarked that he could give a lecture the first time with some enthusiasm, with no enthusiasm the second time, and only with apology the third. Here was revealed a quality of realism and humility none too common in the professorial sphere; also a kind of conflict with his long-confirmed habit of dealing ever with new problems.

During this time, industry was continuing actively to seek his counsel. Although loth to forego these direct contacts with the vibrant world "outside," he was nevertheless unwilling to allow them to embarrass his university work. Finally, with a great deal of reluctance, he resigned from Harvard in 1930, and returned to New York, taking up what proved to be the longest engagement of his career.

With the American Cyanamid Company he had ideal opportunity for the use of his talents in the wide scope of its activities in industrial chemistry. At the time of his death he was a member of the board of directors of the company, chairman of its new projects committee, directly in charge of one of the important producing divisions, and liaison officer between the parent company and affiliated properties engaged in the production of natural raw materials.

After a brief illness of cancer, Wells died at the

Massachusetts General Hospital in Boston on May 24, 1939. In 1907 he had married Charlotte E. Chandler of Brunswick, Me., who survives him at their home in East Orange, New Jersey, together with three sons who have graduated from one or the other of the institutions with which their father was connected.

Wells was known to all his associates as an indefatigable worker. This carried him far. But he also possessed a brilliant mind, effective especially in the analysis of new problems and in grasping their simplest solution. His prime interest was in active accomplishment rather than in the recording of it; but he wrote several important treatises, dealing with sulphur, sulphuric acid, and potash, which were published by the Government. His knowledge covered a surprisingly extended range, and his skill in putting it all to use was shown in his capacities as scientist, research engineer, operator, consultant, educator and executive.

Wells's power was rather that of the quietly spinning dynamo than of the dramatic reciprocating engine. A natural reserve and dignity of manner did not conceal his genial spirit. His capacity for team-work was unusual, and his associates without exception regarded him with esteem and lasting friendship. A vital factor in his conspicuous success was an integrity so inherent that it never needed emphasis.

L. C. Graton

FRANK E. WINSOR (1870–1939)

Fellow in Class I, Section 4, 1933

Frank E. Winsor was born in Providence, Rhode Island, on November 16, 1870, and died in Boston, Massachusetts, on January 30, 1939. He was educated in the public schools of Providence and at Brown University which awarded him the degrees of Bachelor of Philosophy in 1891, Civil Engineer in 1892, Master of Arts in 1895, and Doctor of Science (honorary) in 1929.

Entering engineering practice in 1891, he served on the construction of the Metropolitan Sewerage System of Boston from 1891 to 1895, on the design and construction of the Metropolitan Water Works of Boston from 1895 to 1903 and on the design and construction of the Charles River Dam from 1903 to 1906. From 1906 to 1915, Mr. Winsor was associated with the New York Board of Water Supply on the construction of the Catskill Water Supply System. The Scituate Water Supply of the City of Providence was developed from 1915 to 1926 under his direction. In 1926 Mr. Winsor was appointed Chief Engineer of the Metropolitan District Water Supply Commission of Boston, and he served until the time of his death in bringing in the additional water supply for Metropolitan Boston from the Ware and Swift Rivers. The great earth dam that closes off the Swift River Valley to impound the Quabbin Reservoir has been named the Winsor Dam in his honor.

Endowed with kindness and patience as well as an analytical and judicial mind, his fidelity to all tasks entrusted to him made Mr. Winsor a notable public servant as well as a builder of great and useful public works.

Gordon M. Fair

FREDERICK ADAMS WOODS (1873–1939)

Fellow in Class II, Section 3, 1915

Frederick Adams Woods was distinguished by his work in genetics, especially in tracing the heredity of human character and the effects of this transmission upon the history of nations.

He was born in Boston, January 29, 1873, the son of Solomon Adams Woods (1827–1907), a descendant of Henry Adams (d. Braintree, Mass., 1664), who came from Farmington, Maine, to Boston about 1847 and was a successful inventor and manufacturer of woodworking machinery. His mother, Sarah Catherine Watts, was a studious woman, the daughter of a seafaring man who in later life was devoted to mathematics. Frederick's career was largely determined by this background.

Although living in Brookline, he prepared at the English High School in Boston for the Massachusetts Institute of Technology, where he matriculated in 1890. But he found little of interest in two years of elementary work with not much biology. His intellectual awakening began when he entered the Harvard Medical School in 1894 and came under the influence of Charles Sedgwick Minot, then at the height of his career, working on heredity and rejuvenation and the history of germ-cells. After taking his

M.D. in 1898 Woods was appointed Assistant in Histology, and, besides teaching, helped Minot with his guinea-pigs. In 1899 he began breeding rabbits to obtain a pure black race for crossing with albinos to test Galton's Law of Ancestral Heredity. Four generations gave results which later (1903) furnished material for a paper on Mendel's Laws, with which they were found to be in harmony. Following the lead of Galton, Woods turned to human heredity. His originality and insight are shown by his choice of material, the history of royal families, where he found the best personal and genealogical data. While exploring the College Library for this in old Gore Hall he acquired a delight in books that lasted throughout his life. As early as 1901 at the Chicago meeting of the American Psychological Association he announced his thesis that the influence of environment, as opposed to heredity, in creating mental and moral differences had been overestimated. His evidence appeared in a series of articles in *Popular Science Monthly*, August 1902 to April 1903, followed by one on the correlation between mental and moral qualities. In this and all subsequent work he endeavored to apply quantitative mathematical methods.

In the meantime he was Instructor in the Veterinary School during its last two years (1899–1901) and Instructor in Histology and Embryology in the Medical School, 1901–02. In May 1902 his first printed paper appeared on the "Origin and Migration of Germ-cells in Acanthias" (*Amer. Jour. Anat.*, **1,** 307–320), supporting Weismann's theory of the continuity of the germ-cells and having thus a direct bearing upon the problem of heredity.

In 1903 Woods returned to the Institute of Technology with an annual appointment as Lecturer in Histology and assisted A. W. Weysse. During the next three years he had full charge of instruction in embryology and histology, and afterward lectured occasionally on heredity. He was elected Fellow of the Harvard Travellers Club in 1904, having made a trip around the world. When in Europe he searched in the bookshops and libraries for additional information and portraits to be used in his book, *Mental and Moral Heredity in Royalty* (New York, 1906). He was especially interested in Portugal because there he first observed the correlation between the character of the monarch and the prosperity of the country. When the chief authority on Camoens, Wilhelm Storck, died in 1905, Woods cabled an order to buy his library covering the history of Portugal's Heroic Period. In 1910 Woods was appointed Honorary Curator of Portuguese History in the Harvard College Library. In his second book, *The Influence of Monarchs* (1913), he showed that what was true of Portugal was true of other European countries, except England. His contention was that a major influence in the history of nations is of gametic origin.

Woods was an active member of the American Breeders Association and its successor, the Genetic Association, was member of the Council and Chairman of the Committee on Eugenics, and contributed to the publications of the Association and to other journals. Material that he had been collecting on the prevalence since 1450 of war in Europe was worked over in 1913 and 1914 with the help of Alexander Baltzby. Their book, *Is War Diminishing?*, appeared in 1915. When the entire editorial staff of the *Journal of Heredity* was drafted for the World War, Woods went to Washington and edited the *Journal* from October, 1918, to June, 1919, besides contributing thirteen articles to its pages. At the same time he was appointed, at a-dollar-a-year, Collaborator in the Department of Agriculture, Office of Foreign Seed and Plant Introduction, to gather information of plants eligible for introduction into this country, to review the literature on genetics, and to conduct research; but apparently he did no work in this connection. In 1922 he was a member of the National Research Council.

A chronic bronchitis led Woods to seek a milder climate, and he never resumed residence in Brookline. In 1924 he married the Baroness Marie Thérèse de Lebzeltern-Collenbach, of Austria and New York. After a winter at Port of Spain, Trinidad, and a summer in England, they settled in 1927 at Roma, whence he continued to send contributions to the *Journal of Heredity*. He was Vice-President of the International Congress for Studies Regarding Population Problems at Rome in 1931. He died November 5, 1939.

A pioneer in "Historiometry," the application of statistical methods to the study of the causes and events that are recorded in the histories of nations, he has been called "the American Galton."

R. P. BIGELOW

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11	Simon Flexner	New York, N. Y.
27	James Lawder Gamble	Brookline
22	Joseph Lincoln Goodale	Ipswich
21	Ross Granville Harrison	New Haven, Conn.
27	Percy Rogers Howe	Belmont
21	William Henry Howell	Baltimore, Md.
33	Edgar Erskine Hume	Carlisle, Pa.
15	Reid Hunt	Boston
34	Henry Jackson, Jr.	Chestnut Hill
12	Elliott Proctor Joslin	Boston
23	Roger Irving Lee	Brookline
29	Edwin Allen Locke	Williamstown
28	Warfield Theobald Longcope	Baltimore, Md.
32	Fred Bates Lund	Newton
40	William de Berniere MacNider	Chapel Hill, N. C.
13	Frank Burr Mallory	Brookline
34	Leroy Matthew Simpson Miner	Newtonville
26	George Richards Minot	Brookline
28	William Lorenzo Moss	Athens, Ga.
28	John Howard Mueller	West Roxbury
25	Robert Bayley Osgood	Boston
37	Walter Walker Palmer	New York, N. Y.
27	Joseph Hershey Pratt	Boston
35	Tracy Jackson Putnam	New York, N. Y.
34	William Carter Quinby	Brookline
34	Arthur Hiler Ruggles	Providence, R. I.
39	Frederick Fuller Russell	Brookline
39	William Thomas Salter	Milton
27	Andrew Watson Sellards	Boston
33	George Cheever Shattuck	Brookline
30	Torald Hermann Sollmann	Cleveland, Ohio
21	Charles Wardell Stiles	Washington, D. C.

14	Richard Pearson Strong	Boston
30	Fritz Bradley Talbot	Brookline
14	Ernest Edward Tyzzer	Wakefield
40	Donald Dexter Van Slyke	New York, N. Y.
14	Frederick Herman Verhoeff	Brookline
27	Joseph Treloar Wearn	Cleveland, Ohio
33	Soma Weiss	Cambridge
40	Paul Dudley White	Brookline
12	Simeon Burt Wolbach	South Sudbury

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SECTION I—*Jurisprudence*—44

(24) 32	Francis Noyes Balch	Jamaica Plain
38	Henry Moore Bates	Ann Arbor, Mich.
06	Joseph Henry Beale	Cambridge
36	Stoughton Bell	Cambridge
33	Harry Augustus Bigelow	Chicago, Ill.
33	Henry Wolf Biklé	Philadelphia, Pa.
36	Wilfred Bolster	Wellesley
36	Claude Raymond Branch	Providence, R. I.
33	John Dickinson	Philadelphia, Pa.
38	Robert Gray Dodge	Boston
31	Fred Tarbell Field	Newton
39	Herbert Funk Goodrich	Philadelphia, Pa.
33	Theodore Francis Green	Providence, R. I.
38	Frank Washburn Grinnell	Boston
39	John Loomer Hall	Boston
39	Augustus Noble Hand	New York, N. Y.
33	Learned Hand	New York, N. Y.
39	Albert James Harno	Urbana, Ill.
18	Charles Evans Hughes	Washington, D. C.
31	Nathan Isaacs	Cambridge
38	Melvin Maynard Johnson	Brookline
38	James McCauley Landis	Cambridge
21	Frederick Lawton	Boston
32	Sayre Macneil	Azusa, Cal.
32	Calvert Magruder	Cambridge
31	William DeWitt Mitchell	New York, N. Y.
31	Edmund Morris Morgan	Arlington
36	Henry Parkman, Jr.	Boston
39	Robert Porter Patterson	New York, N. Y.
01	George Wharton Pepper	Philadelphia, Pa.
11	Roscoe Pound	Watertown
38	William Morton Prest	Boston
36	Stanley Elroy Qua	Lowell
32	Francis Bowes Sayre	Manila, P. I.
21	Austin Wakeman Scott	Cambridge
35	James Brown Scott	Washington, D. C.
36	Sidney Post Simpson	Cambridge
33	Harlan Fiske Stone	Washington, D. C.
39	Thomas Walter Swan	New York, N. Y.
32	Edward Sampson Thurston	Cambridge
14	Eugene Wambaugh	Cambridge
38	Bentley Wirt Warren	Boston
37	Joseph Warren	Brookline
(28) 32	Edmund Allen Whitman	Cambridge

CLASS III, SECTION II—*Government, International Law, and Diplomacy*—25

36	Howard Landis Bevis	Columbus, O.
33	Edwin Montefiore Borchard	New Haven, Conn.
40	Robert Granville Caldwell	Belmont
32	William Richards Castle, Jr.	Washington, D. C.
32	Joseph Perkins Chamberlain	New York, N. Y.
33	Robert Treat Crane	New York, N. Y.
35	Tyler Dennett	Hague, N. Y.
31	Sidney Bradshaw Fay	Cambridge
27	William Cameron Forbes	Norwood
34	Edgar Stephenson Furniss	New Haven, Conn.
32	Joseph Clark Grew	Tokyo, Japan
35	Charles Grove Haines	Los Angeles, Cal.
16	Albert Bushnell Hart	Cambridge
27	Arthur Norman Holcombe	Cambridge
31	Manley Ottmer Hudson	Cambridge
32	Philip Carryl Jessup	New York, N. Y.
97	Abbott Lawrence Lowell	Boston
32	Charles Edward Merriam	Chicago, Ill.
19	John Bassett Moore	New York, N. Y.
13	William Bennett Munro	Pasadena, Cal.
27	Westel Woodbury Willoughby	Washington, D. C.
32	William Franklin Willoughby	Washington, D. C.
14	George Grafton Wilson	Grafton, Vt.
27	Quincy Wright	Chicago, Ill.
33	Henry Aaron Yeomans	Cambridge

CLASS III, SECTION III—*Economics and Sociology*—63

36	James Waterhouse Angell	New York, N. Y.
36	James Cummings Bonbright	New York, N. Y.
33	Harold Hitchings Burbank	Cambridge
36	Philip Cabot	Milton
36	Edward Hastings Chamberlin	Cambridge
34	John Maurice Clark	Westport, Conn.
28	Arthur Harrison Cole	Cambridge
31	Melvin Thomas Copeland	Cambridge
31	William Leonard Crum	Cambridge
32	William James Cunningham	Cambridge
34	Winthrop More Daniels	Saybrook Point, Conn.
21	Clive Day	New Haven, Conn.
13	Davis Rich Dewey	Cambridge
32	Arthur Stone Dewing	Newton
32	Wallace Brett Donham	Boston
34	John Franklin Ebersole	Belmont
36	Fred Rogers Fairchild	New Haven, Conn.
36	Frank Albert Fetter	Princeton, N. J.
12	Irving Fisher	New Haven, Conn.
31	James Ford	Cambridge
34	Ralph Evans Freeman	Cambridge
13	Edwin Francis Gay	Pasadena, Cal.
33	Sheldon Glueck	Cambridge
39	Gottfried Haberler	Cambridge
34	Robert Murray Haig	New York, N. Y.
32	Henry Wyman Holmes	Cambridge
34	Edwin Walter Kemmerer	Princeton, N. J.
34	Frank Hyneman Knight	Chicago, Ill.
36	Roswell Cheney McCrea	New York, N. Y.

34 Robert Morison MacIver.......New York, N. Y.
32 Walter Wallace McLaren..........Williamstown
36 Malcolm Perrine McNair.............Cambridge
32 Leon Carroll Marshall.........Chevy Chase, Md.
33 Edward Sagendorph Mason...........Cambridge
36 Elton Mayo..........................Cambridge
34 Richard Stockton Meriam..........South Lincoln
34 Harry Alvin Millis..................Chicago, Ill.
32 Frederick Cecil Mills...........New York, N. Y.
31 Wesley Clair Mitchell..........New York, N. Y.
34 Arthur Eli Monroe..................Cambridge
32 Harold Glenn Moulton........Washington, D. C.
34 Edwin Griswold Nourse.......Washington, D. C.
32 William Fielding Ogburn............Chicago, Ill.
33 Robert Ezra Park...............Nashville, Tenn.
32 Leo S. Rowe..................Washington, D. C.
37 Clyde Orval Ruggles.................Cambridge
36 Thomas Henry Sanders..............Cambridge
33 Josef Alois Schumpeter...............Cambridge
32 Carl Snyder...................New York, N. Y.
31 Pitirim Alexandrovich Sorokin........Winchester
31 Oliver Mitchell Wentworth Sprague....Cambridge
(89) 01 Frank William Taussig..........Cambridge
34 Frederick John Teggart............Berkeley, Cal.
33 William Isaac Thomas..........New York, N. Y.
37 Harry Rudolph Tosdal................Belmont
31 Donald Skeele Tucker..................Belmont
33 Abbott Payson Usher...............Cambridge
34 Jacob Viner.......................Chicago, Ill.
38 T[homas] North Whitehead..........Cambridge
32 John Henry Williams...............Cambridge
36 Joseph Henry Willits...........New York, N. Y.
34 Leo Wolman..................New York, N. Y.
34 Carle Clark Zimmerman.............Winchester

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(25) 32 Charles Francis Adams.............Concord
39 Chester Irving Barnard............Newark, N. J.
(25) 32 Charles Foster Batchelder........Cambridge
38 Edmund Ezra Day................Ithaca, N. Y.
32 Henry Sturgis Dennison............Framingham
(28) 32 William Lusk Webster Field.........Milton
39 Ralph Edward Flanders..........Springfield, Vt.
38 Horace Sayford Ford..................Belmont
35 Jerome Davis Greene................Cambridge
39 Henry Ingraham Harriman.......Newton Center
(28) 32 Edward Jackson Holmes............Boston
34 Henry Plimpton Kendall................Walpole
32 Thomas William Lamont.......New York, N. Y.
39 Morris Evans Leeds............Philadelphia, Pa.
34 Clarence Cook Little............Bar Harbor, Me.
36 Dumas Malone.....................Cambridge
33 James Vance May..................Watertown
02 Herbert Putnam.............Washington, D. C.
(28) 32 Alfred Lawrence Ripley............Andover
34 Erwin Haskell Schell.................Cambridge
38 Charles Seymour.............New Haven, Conn.
35 Henry Lee Shattuck.....................Boston
37 Henry Southworth Shaw...........Exeter, N. H.

(28) 32 Payson Smith...................Brookline
33 Albert Warren Stearns.................Billerica
(25) 32 Charles Henry Taylor..............Boston
36 Clair Elsmere Turner..................Arlington
(24) 32 Edwin Sibley Webster...........Brookline
(25) 32 Benjamin Loring Young...........Weston
39 Owen D. Young...............New York, N. Y.

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32 Michael Joseph Ahern..................Weston
33 Gordon Willard Allport..............Cambridge
32 James Rowland Angell........New Haven, Conn.
33 John Gilbert Beebe-Center..........Swampscott
38 Julius Seelye Bixler.................Cambridge
24 Edwin Garrigues Boring.............Cambridge
28 Edgar Sheffield Brightman..............Newton
31 Henry Addington Bruce.............Cambridge
32 Leonard Carmichael..............Tufts College
36 Robert Pierce Casey............Providence, R. I.
33 J[ames] McKeen Cattell..........Garrison, N. Y.
28 Walter Fenno Dearborn.............Cambridge
18 Edmund Burke Delabarre.......Providence, R. I.
24 Raymond Dodge..................Tryon, N. C.
33 Curt John Ducasse.............Providence, R. I.
38 James Everett Frame............Princeton, N. J.
37 Clarence Henry Graham........Providence, R. I.
30 William Henry Paine Hatch..........Cambridge
32 William Healy.........................Boston
10 William Arthur Heidel........Middletown, Conn.
21 William Ernest Hocking.............Cambridge
35 Clark Leonard Hull..........New Haven, Conn.
33 Walter Samuel Hunter..........Providence, R. I.
17 Frederick John Foakes Jackson..Englewood, N. J.
28 Albert Cornelius Knudson............Cambridge
34 Kurt Koffka......................Northampton
32 Karl Spencer Lashley.................Belmont
13 William Lawrence......................Boston
29 Clarence Irving Lewis.................Lexington
33 Lee Sullivan McCollester...........Tufts College
10 Edward Caldwell Moore..............Cambridge
35 Henry Alexander Murray, Jr.............Boston
32 Arthur Darby Nock.................Cambridge
32 William Cardinal O'Connell..............Boston
28 Johnson O'Connor......................Boston
17 Charles Edwards Park..................Boston
33 Carroll Cornelius Pratt.....New Brunswick, N. J.
30 James Hugh Ryan.................Omaha, Neb.
31 Henry Knox Sherrill.....................Boston
27 Willard Learoyd Sperry..............Cambridge
29 Russell Henry Stafford................Brookline
34 Lewis Madison Terman..Stanford University, Cal.
34 Edward Lee Thorndike.........New York, N. Y.
37 Louis Leon Thurstone...............Chicago, Ill.
28 Henry Bradford Washburn............Cambridge
17 John Broadus Watson..........New York, N. Y.
33 Frederic Lyman Wells.........Newton Highlands
35 Robert Sessions Woodworth.....New York, N. Y.
15 Robert Mearns Yerkes........New Haven, Conn.

Class IV, Section II—*History, Archaeology, and Anthropology*—42

18 Charles McClean Andrews.....New Haven, Conn.
28 James Phinney Baxter, 3d..........Williamstown
23 Carl Lotus Becker..................Ithaca, N. Y.
27 Robert Pierpont Blake...............Cambridge
12 Franz Boas....................New York, N. Y.
39 Crane Brinton.......................Cambridge
(25) 32 William Brooks Cabot..............Boston
34 Clarence Gordon Campbell......New York, N. Y.
12 George Henry Chase.................Cambridge
21 Max Farrand...................San Marino, Cal.
21 William Scott Ferguson..............Cambridge
38 Allyn Bailey Forbes.................Cambridge
10 Worthington Chauncey Ford..........Cambridge
33 Henry Thatcher Fowler..........Providence, R. I.
38 Claude Moore Fuess...................Andover
18 Evarts Boutell Greene..........New York, N. Y.
19 Charles Downer Hazen.........New York, N. Y.
14 Bert Hodge Hill..................Athens, Greece
27 Earnest Albert Hooton...............Cambridge
33 Halford Lancaster Hoskins.........Tufts College
15 Aleš Hrdlička.................Washington, D. C.
12 Alfred Louis Kroeber...............Berkeley, Cal.
15 Kirsopp Lake......................Haverford, Pa.
22 George LaPiana......................Cambridge
32 Waldo Gifford Leland.........Washington, D. C.
20 Charles Howard McIlwain...............Belmont
14 Roger Bigelow Merriman.............Cambridge
38 Stewart Mitchell.....................Gloucester
15 Samuel Eliot Morison...................Boston
34 Robert Henry Pfeiffer...............Cambridge
14 George Andrew Reisner..................Boston
34 David Moore Robinson...........Baltimore, Md.
23 Michael Ivanovich Rostovtzeff..New Haven, Conn.
27 George Sarton.......................Cambridge
38 Bernadotte Everly Schmitt..........Chicago, Ill.
36 Donald Scott........................Cambridge
34 Theodore Leslie Shear............Princeton, N. J.
26 Herbert Joseph Spinden..........Brooklyn, N. Y.
32 Charles Holt Taylor.................Cambridge
11 Alfred Marston Tozzer..............Cambridge
39 Henry Rouse Viets.....................Dedham
20 Clark Wissler..................New York, N. Y.

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31 Edward Cooke Armstrong........Princeton, N. J.
33 William Nickerson Bates........Philadelphia, Pa.
35 Charles Henry Beeson..............Chicago, Ill.
33 Campbell Bonner..............Ann Arbor, Mich.
35 Robert Johnson Bonner.............Chicago, Ill.
33 Carleton Brown................New York, N. Y.
21 Carl Darling Buck..................Chicago, Ill.
18 Edward Capps.....................Princeton, N. J.
20 Walter Eugene Clark................Cambridge
32 Ronald Salmon Crane...............Chicago, Ill.
32 Morris William Croll............Princeton, N. J.
31 Samuel Hazzard Cross...............Cambridge
20 Franklin Edgerton............New Haven, Conn.
40 Serge Elisséeff........................Cambridge
21 Frank Edgar Farley..........Middletown, Conn.
14 Jeremiah Denis Mathias Ford.........Cambridge
30 James Geddes, Jr.....................Brookline
16 Louis Herbert Gray............New York, N. Y.
25 William Chase Greene.................Cambridge
13 Charles Burton Gulick...............Cambridge
19 Roy Kenneth Hack.............Cincinnati, Ohio
34 Austin Morris Harmon........New Haven, Conn.
31 Raymond Dexter Havens.........Baltimore, Md.
38 Richmond Laurin Hawkins...........Cambridge
18 George Lincoln Hendrickson...New Haven, Conn.
17 William Guild Howard...............Cambridge
21 Eugene Xavier Louis Henry Hyvernat, Wash., D.C.
15 Carl Newell Jackson.................Cambridge
40 Werner Wilhelm Jaeger..............Watertown
13 James Richard Jewett...............Cambridge
32 (Ralph) Hayward Keniston..........Chicago, Ill.
34 Roland Grubb Kent............Wynnewood, Pa.
98 George Lyman Kittredge.............Cambridge
33 Hans Kurath..................Providence, R. I.
39 Henry Carrington Lancaster......Baltimore, Md.
32 Ernest Felix Langley................Cambridge
[81] 98 Charles Rockwell Lanman.........Cambridge
33 Ivan Mortimer Linforth...........Berkeley, Cal.
11 Albert Matthews........................Boston
35 Benjamin Dean Meritt...........Princeton, N. J.
28 William Albert Nitze...............Chicago, Ill.
32 George Rapall Noyes..............Berkeley, Cal.
34 William Abbott Oldfather............Urbana, Ill.
33 Howard Rollin Patch..............Northampton
32 Arthur Stanley Pease.................Cambridge
35 Henry Washington Prescott..........Chicago, Ill.
13 Edward Kennard Rand...............Cambridge
11 Fred Norris Robinson................Cambridge
38 Hyder Edward Rollins...............Cambridge
31 Robert Kilburn Root.............Princeton, N. J.
35 Henry Arthur Sanders..........Ann Arbor, Mich.
18 Rudolph Schevill..................Berkeley, Cal.
32 Horatio Elwin Smith............New York, N. Y.
40 Edgar Howard Sturtevant.....New Haven, Conn.
39 John Strong Perry Tatlock.........Berkeley, Cal.
32 William Thomson......................Cambridge
11 Charles Cutler Torrey.........New Haven, Conn.
33 George Benson Weston...............Cambridge
30 Ernest Hatch Wilkins..............Oberlin, Ohio
33 Harry Austryn Wolfson..............Cambridge
39 William Hoyt Worrell..........Ann Arbor, Mich.
33 Karl Young...................New Haven, Conn.

Class IV, Section IV—*The Fine Arts and Belles Lettres*—51

31 Stephen Vincent Benét.........New York, N. Y.
26 Frank Weston Benson....................Salem
32 (William) Welles Bosworth.....New York, N. Y.
33 John Alden Carpenter...............Chicago, Ill.
32 Chalmers Dancy Clifton.........Westport, Conn.
32 Kenneth John Conant................Cambridge

34 Charles Jay Connick................Newtonville
29 Charles Townsend Copeland..........Cambridge
[17] 30 Ralph Adams Cram.................Boston
33 Cyrus Edwin Dallin............Arlington Heights
34 Samuel Foster Damon..........Providence, R. I.
32 George Harold Edgell................Cambridge
21 William Emerson...................Cambridge
33 Carl Engel....................New York, N. Y.
30 John Erskine..................New York, N. Y.
10 Arthur Fairbanks...............Hanover, N. H.
18 Edward Waldo Forbes................Cambridge
31 Robert Frost.............South Shaftsbury, Vt.
27 Wallace Goodrich......................Boston
36 William Clifford Heilman............Cambridge
29 Edward Burlingame Hill.............Cambridge
31 Robert Silliman Hillyer..............Cambridge
27 Charles Hopkinson.................Manchester
12 Mark Antony DeWolfe Howe............Boston
38 Joseph Hudnut........................Boston
18 Archer Milton Huntington......New York, N. Y.
31 Henry James..................New York, N. Y.
(25) 32 William James.................Cambridge
38 Howard Mumford Jones.............Cambridge
33 Leo Rich Lewis..................Tufts College
20 John Ellerton Lodge..........Washington, D. C.
21 John Livingston Lowes..............Cambridge
21 Charles Donagh Maginnis.............Brookline
31 Paul Manship.................New York, N. Y.
31 Daniel Gregory Mason.........New York, N. Y.
31 Frank Jewett Mather...Washington Crossing, Pa.
31 Kenneth Ballard Murdock............Cambridge
14 William Allan Neilson.......Falls Village, Conn.
28 Curtis Hidden Page............Gilmanton, N. H.
21 William Lyon Phelps.........New Haven, Conn.
(24) 32 Anthony John Philpott...........Arlington
21 Chandler Rathfon Post..............Cambridge
22 Paul Joseph Sachs..................Cambridge
14 Ellery Sedgwick.......................Boston
19 Henry Dwight Sedgwick................Dedham
33 David Stanley Smith.........Woodbridge, Conn.
35 Walter Raymond Spalding...........Cambridge
39 Francis Henry Taylor..........New York, N. Y.
39 Karl Ephraim Weston.............Williamstown
38 Grenville Lindall Winthrop................Lenox
22 Charles Henry Conrad Wright.........Cambridge

FOREIGN HONORARY MEMBERS—128

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CLASS I—MATHEMATICAL AND PHYSICAL SCIENCES—32

SECTION I—*Mathematics and Astronomy*—10

39	Arnaud Denjoy	Paris
22	Sir Arthur Stanley Eddington	Cambridge, England
34	Ronald Aylmer Fisher	Harpenden, Herts
20	Jacques Salomon Hadamard	Paris
21	Godfrey Harold Hardy	Cambridge, England
27	Ejnar Hertzsprung	Leyden
17	Tullio Levi-Civita	Rome
03	Charles Émile Picard	Paris
15	Charles Jean de la Vallée Poussin	Louvain
29	Hermann Weyl	Princeton, N. J.

CLASS I, SECTION II—*Physics*—8

29	Vilhelm Frimann Koren Bjerknes	Oslo
24	Albert Einstein	Princeton, N. J.
29	James Franck	Baltimore, Md.
29	Abram F. Joffé	Leningrad
03	Sir Joseph Larmor	Cambridge, England
28	Friedrich Paschen	Charlottenburg
14	Max Planck	Berlin
02	Sir Joseph John Thomson	Cambridge, England

CLASS I, SECTION III—*Chemistry*—8

29	Johannes N. Brönsted	Copenhagen
27	Peter Debye	Berlin
33	Jaroslav Heyrovsky	Prague
33	Fritz Paneth	Durham
38	Leopold Ruzicka	Zürich
38	Nevil Vincent Sidgwick	Oxford
29	Heinrich Wieland	Munich
34	Richard Willstätter	Muralto-Locarno, Switzerland

CLASS I, SECTION IV—*Technology and Engineering*—6

36	Edward Victor Appleton	London
34	Luigi Lombardi	Rome
29	Ludwig Prandtl	Göttingen
29	Emil Probst	Oxford
29	Aurel Stodola	Zürich
31	Karl Willy Wagner	Berlin

CLASS II—NATURAL AND PHYSIOLOGICAL SCIENCES—31

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17	Frank Dawson Adams	Montreal
36	Raoul Blanchard	Grenoble, France
29	Léon William Collet	Geneva
34	Arthur Holmes	Durham
22	Emmanuel de Margerie	Paris
21	Gustaf Adolf Frederik Molengraaff	Delft
18	Sir William Napier Shaw	London

CLASS II, SECTION II—*Botany*—6

32	Frederick Orpen Bower	Ripon
31	Ludwig Diels	Berlin
32	Kingo Miyâbe	Sapporo, Japan
29	Otto Renner	Jena
32	Sir Albert Charles Seward	London
35	Sir William Wright Smith	Edinburgh

CLASS II, SECTION III—*Zoology and Physiology*—10

38	Edgar Douglas Adrian	Cambridge, England
38	Sir Joseph Barcroft	Cambridge, England
20	Maurice Caullery	Paris
38	Emmanuel Fauré-Frémiet	Paris
34	Archibald Vivian Hill	London
31	August Krogh	Copenhagen
30	Louis Édouard Lapicque	Paris
28	Charles Tate Regan	Feltham, Middlesex
33	Hans Spemann	Freiburg i. Br.
28	Sir D'Arcy Wentworth Thompson	St. Andrews

CLASS II, SECTION IV—*Medicine and Surgery*—8

18	Sir Thomas Barlow, Bart	London
39	Sir Aldo Castellani	Rome
27	Sir Henry Hallett Dale	London
33	Sir Arthur Keith	London
28	Mikinosuke Miyajima	Tokyo
27	Friedrich von Müller	Munich
18	Sir Charles Scott Sherrington	Ipswich, England
36	(Jean) Hyacinthe Vincent	Paris

CLASS III—THE SOCIAL ARTS—35

SECTION I—*Jurisprudence*—15

39	Rt. Hon. Lord Atkin	London
38	William Warwick Buckland	Cambridge, England
38	Mircea Djuvara	Bucharest
27	Léon Duguit	Bordeaux
33	François Geny	Nancy
38	Arthur Lehman Goodhart	Oxford
39	Rt. Hon. Sir Wilfrid Arthur Greene	London
39	Sir William Searle Holdsworth	Oxford
33	Hans Kelsen	Vienna
38	Rt. Hon. Lord Macmillan	London
33	Juljusz Makarewicz	Lwów
33	Rudolph Stammler	Wernigerode a. H.
33	Giorgio Del Vecchio	Rome
38	Rt. Hon. Lord Wright	London
38	John C. H. Wu	Hong Kong

SECTION II—*Government, International Law, and Diplomacy*—4

38	Dionisio Anzilotti	Rome
32	Paul Claudel	Paris
32	Hu Shih	Washington, D. C.
38	Kenzo Takayanagi	Tokyo

SECTION III—*Economics and Sociology*—12

32	Arthur Lyon Bowley	Haslemere, Surrey
34	Gustav Cassel	Djursholm, Sweden
39	Henry Clay	Kenley, Surrey
35	Luigi Einaudi	Turin
32	Ralph George Hawtrey	London
35	John Maynard Keynes	Cambridge, England
35	René Maunier	Paris
28	Arthur Cecil Pigou	Cambridge, England
32	Charles Rist	Fraisses (Loire)
33	Werner Sombart	Berlin
35	S. Rudolph Steinmetz	Amsterdam
34	Peter B. Struve	Belgrade

SECTION IV—*Administration and Affairs*—4

33	Gösta A. Bagge	Stockholm
38	Heinrich Brüning	Cambridge, Mass.
38	B. Seebohm Rowntree	North Dean, Bucks
33	Josiah Charles Stamp, Baron Stamp,	Shortlands, Kent

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36	Miguel Asín y Palacios	Madrid
28	Henri Louis Bergson	Paris
28	Benedetto Croce	Naples
29	Étienne Gilson	Melun
28	Edmund Husserl	Freiburg i. B.
32	Pierre Janet	Paris
28	Wolfgang Köhler	Berlin
37	Henri Pieron	Paris

SECTION II—*History, Archaeology, and Anthropology*—6

33	Rafael Altamira y Crevea	Madrid
36	Marcel Aubert	Paris
29	Godfrey R. Benson, Baron Charnwood	London
33	Friedrich Meinecke	Berlin-Dahlem
30	Sir Aurel Stein	Srinagar, Kashmir
31	George Macaulay Trevelyan	Cambridge, England

SECTION III—*Philology*—6

09	Hermann Georg Jacobi	Bonn
36	Paul Kretschmer	Vienna
32	Paul Mazon	Paris
[12] 28	Hanns Oertel	Munich
17	Ramón Menéndez Pidal	Madrid
32	Frederick William Thomas	Oxford

SECTION IV—*The Fine Arts and Belles Lettres*—10

40	Fernand Baldensperger	Pari
30	Alfredo Casella	Rom
23	Henry Guy	Grenobl
29	Paul Hazard	Pari
40	Paul Hindemith	New Haven, Conn
34	Serge Koussevitzky	Paris and Bosto
27	Gilbert Murray	Oxfor
31	Edgar Allison Peers	Liverpoo
27	Henri Rabaud	Pari
40	Igor Strawinsky	Pari

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The letters F and FHM refer to the lists of Fellows and Foreign Honorary Members, respectively. The class and section are indicated by the numerals following.

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Bailey, L. H. F, II: 2
Bainbridge, K. T. F, I: 2
Balch, F. G. F, II: 4
Balch, F. N. F, III: 1
Baldensperger, F. FHM, IV: 4
Bancroft, W. D. F, I: 3
Banks, N. F, II: 3
Barbour, T. F, II: 3
Barcroft, Sir J. FHM, II: 3
Bard, P. F, II: 3
Barlow, Sir T. FHM, II: 4
Barnard, C. I. F, III: 4
Barnett, S. J. F, I: 2
Barrows, H. K. F, I: 4
Batchelder, C. F. F, III: 4
Bates, H. M. F, III: 1
Bates, W. N. F, IV: 3
Baxter, G. P. F, I: 3
Baxter, J. P., 3d. F, IV: 2
Beale, J. H. F, III: 1
Beattie, J. A. F, I: 3
Becker, C. L. F, IV: 2
Beebe-Center, J. G. F, IV: 1
Beeson, C. H. F, IV: 3
Bell, S. F, III: 1
Benedict, F. G. F, II: 3
Benét, S. V. F, IV: 4
Bennett, A. A. F, I: 1
Benson, F. W. F, IV: 4
Bergson, H. L. FHM, IV: 1
Berry, C. H. F, I: 4
Berry, E. W. F, II: 2
Bevis, H. L. F, III: 2
Bigelow, H. A. F, III: 1
Bigelow, H. B. F, II: 3
Bigelow, R. P. F, II: 3
Biklé, H. W. F, III: 1
Billings, M. P. F, II: 1
Birkhoff, G. D. F, I: 1
Bixler, J. S. F, IV: 1
Bjerknes, V. F. K. FHM, I: 2
Blake, C. H. F, II: 3
Blake, R. P. F, IV: 2
Blanchard, A. A. F, I: 3
Blanchard, R. FHM, II: 1
Bliss, G. A. F, I: 1
Blumer, G. F, II: 4
Boas, F. F, IV: 2
Bogert, M. T. F, I: 3
Bok, B. J. F, I: 1
Bolster, W. F, III: 1
Bonbright, J. C. F, III: 3
Bonner, C. F, IV: 3
Bonner, R. J. F, IV: 3
Booth, H. S. F, I: 3
Borchard, E. M. F, III: 2
Boring, E. G. F, IV: 1
Bosworth, W. F, IV: 1
Bovie, W. T. F, II: 3
Bowen, N. L. F, II: 1
Bower, F. O. FHM, II: 2
Bowley, A. L. FHM, III: 3
Bowman, I. F, II: 1
Boyden, E. A. F, II: 3
Branch, C. R. F, III: 1
Bray, W. C. F, I: 3
Bremer, J. L. F, II: 3
Bridgman, P. W. F, I: 2
Briggs, L. J. F, I: 2
Brightman, E. S. F, IV: 1
Brinton, C. F, IV: 2
Brönsted, J. N. FHM, I: 3
Brooks, C. F. F, II: 1
Brown, C. F, IV: 3
Bruce, H. A. F, IV: 1
Brüning, H. FHM, III: 4
Brues, C. T. F, II: 3
Bryan, K. F, II: 1
Buck, C. D. F, IV: 3
Buckland, W. W. FHM, III: 1
Bunker, J. W. M. F, II: 3
Burbank, H. H. F, III: 3
Burwell, C. S. F, II: 4
Bush, V. F, I: 4
Cabot, P F, III: 3
Cabot, W. B. F, IV: 2
Cady, W. G. F, I: 2
Caldwell, R. G. F, III: 2
Campbell, C. G. F, IV: 2
Campbell, C. M. F, II: 4
Campbell, D. H. F, II: 2
Campbell, G. A. F, I: 2
Campbell, L. L. F, I: 2
Cannon, W. B. F, II: 3
Capps, E. F, IV: 3
Carmichael, L. F, IV: 1
Carpenter, F. M. F, II: 1
Carpenter, J. A. F, IV: 4
Carpenter, T. M. F, II: 3
Carrel, A. F, II: 4
Casella, A. FHM, IV: 4
Casey, R. P. F, IV: 1
Cassel, G. FHM, III: 3
Castle, W. B. F, II: 4
Castellani, Sir A. FHM, II: 4
Castle, W. E. F, II: 3
Castle, W. R., Jr. F, III: 2
Cattell, J. M. F, IV: 1
Caullery, M. FHM, II: 3
Chaffee, E. L. F, I: 2
Chamberlain, J. P. F, III: 2
Chamberlin, D. H. F, III: 3
Chamot, E. M. F, I: 3
Chapin, C. V. F, II: 4
Charnwood, Lord. FHM, IV: 2
Chase, G. H. F, IV: 2

Cheever, D. F, II: 4
Chittenden, R. H. F, I: 3
Christian, H. A. F, II: 4
Clark, J. M. F, III: 3
Clark, W. E. F, IV: 3
Claudel, P. FHM, III: 2
Clay, H. FHM, III: 3
Clayton, H. H. F, II: 1
Cleveland, L. R. F, II: 3
Clifton, C. D. F, IV: 4
Cohn, E. J. F, II: 3
Cole, A. H. F, III: 3
Cole, R. F, II: 4
Collet, L. W. FHM, II: 1
Compton, A. H. F, I: 2
Compton, K. T. F, I: 2
Comstock, D. F. F, I: 2
Conant, J. B. F, I: 3
Conant, K. J. F, IV: 4
Conklin, E. G. F, II: 3
Connick, C. J. F, IV: 4
Coolidge, J. L. F, I: 1
Coolidge, W. D. F, I: 2
Copeland, C. T. F, IV: 4
Copeland, M. F, II: 3
Copeland, M. T. F, III: 3
Cram, R. A. F, IV: 4
Crane, R. S. F, IV: 3
Crane, R. T. F, III: 2
Crawford, F. H. F, I: 2
Crew, H. F, I: 2
Croce, B. FHM, IV: 1
Croll, M. W. F, IV: 3
Cross, S. H. F, IV: 3
Crozier, W. J. F, II: 3
Crum, W. L. F, III: 3
Cunningham, W. J. F, III: 3
Cushman, J. A. F, II: 3
Cutler, E. C. F, II: 4
Dahl, O. G. C. F, I: 4
Dale, Sir H. H. FHM, II: 4
Dallin, C. E. F, IV: 4
Daly, R. A. F, II: 1
Damon, S. F. F, IV: 4
Daniel, J. F. F, II: 3
Daniels, W. M. F, III: 3
Davenport, C. B. F, II: 3
Davis, B. M. F, II: 2
Davis, H. F, II: 3
Davis, H. N. F, I: 2
Davis, T. L. F, I: 3
Davisson, C. J. F, I: 2
Dawes, C. L. F, I: 4
Dawson, A. B. F, II: 3
Day, A. L. F, I: 2
Day, C. F, III: 3
Day, E. E. F, III: 4
Dearborn, W. F. F, IV: 1
Debye, P. FHM, I: 3
de Forest, A. V. F, I: 4

Delabarre, E. B. F, IV: 1
Den Hartog, J. P. F, I: 4
Denjoy, A. FHM, I: 1
Dennett, T. F, III: 2
Dennison, H. S. F, III: 4
Detwiler, S. R. F, II: 3
Dewey, D. R. F, III: 3
Dewing, A. S. F, III: 3
Dickinson, J. F, III: 1
Dickson, L. E. F, I: 1
Diels, L. FHM, II: 2
Dillon, T. H. F, I: 4
Djuvara, M. FHM, III: 1
Dodge, B. O. F, II: 2
Dodge, R. F, IV: 1
Dodge, R. G. F, III: 1
Donham, W. B. F, III: 3
Douglas, J. F, I: 1
Drinker, P. F, I: 4
Drisko, W. J. F, I: 2
Du Bois, E. F. F, II: 4
Ducasse, C. J. F, IV: 1
Duff, A. W. F, I: 2
Duguit, L. FHM, III: 1
Duncan, J. C. F, I: 1
Dunn, G. F, I: 4
Durand, W. F. F, I: 4
Ebersole, J. F. F, III: 3
Eddington, Sir A. S. FHM, I: 1
Edgell, G. H. F, IV: 4
Edgerton, F. F, IV: 3
Edsall, J. T. F, I: 3
Einaudi, L. FHM, III: 3
Einstein, A. FHM, I: 2
Elisséeff, S. F, IV: 3
Emerson, R. A. F, II: 2
Emerson, W. F, IV: 4
Engel, C. F, IV: 4
Erskine, J. F, IV: 4
Esselen, G. J. F, I: 3
Evans, A. W. F, II: 2
Evans, G. C. F, I: 1
Evans, H. M. F, II: 3
Evans, W. L. F, I: 3
Ewell, A. W. F, I: 2
Fair, G. M. F, I: 4
Fairbanks, A. F, IV: 4
Fairchild, F. R. F, III: 3
Farley, F. E. F, IV: 3
Farnsworth, H. E. F, I: 2
Farrand, M. F, IV: 2
Faull, J. H. F, II: 2
Fauré-Frémiet, E. FHM, II: 3
Fay, F. H. F, I: 4
Fay, S. B. F, III: 2
Ferguson, W. S. F, IV: 2
Fergusson, S. P. F, II: 1
Fernald, M. L. F, II: 2
Fetter, F. A. F, III: 3
Field, F. T. F, III: 1

Field, W. L. W. F, III: 4
Fieser, L. F. F, I: 3
Fisher, I. F, III: 3
Fisher, R. A. FHM, I: 1
Fiske, C. H. F, II: 3
Fitz, R. F, II: 4
Flanders, R. E. F, III: 4
Flexner, S. F, II: 4
Forbes, A. F, II: 3
Forbes, A. B. F, IV: 2
Forbes, E. W. F, IV: 4
Forbes, G. S. F, I: 3
Forbes, W. C. F, III: 2
Ford, H. S. F, III: 4
Ford, J. F, III: 3
Ford, J. D. M. F, IV: 3
Ford, W. C. F, IV: 2
Fowler, H. T. F, IV: 2
Fox, P. F, I: 1
Frame, J. E. F, IV: 1
Franck, J. FHM, I: 2
Franklin, P. F, I: 1
Freeman, R. E. F, III: 3
Frost, R. F, IV: 4
Fuess, C. M. F, IV: 2
Fulton, J. F. F, II: 3
Furniss, E. S. F, III: 2
Gamble, J. L. F, II: 4
Gay, E. F. F, III: 3
Geddes, J., Jr. F, IV: 3
Geny, F. FHM, III: 1
Gilboy, G. F, I: 4
Gillespie, L. J. F, I: 3
Gilson, E. FHM, IV: 1
Glueck, S. F, III: 3
Goldthwait, J. W. F, II: 1
Goodale, J. L. F, II: 4
Goodhart, A. L. FHM, III: 1
Goodrich, H. F. F, III: 1
Goodrich, W. F, IV: 4
Goodwin, H. M. F, I: 2
Graham, C. H. F, IV: 1
Graton, L. C. F, II: 1
Graustein, W. C. F, I: 1
Gray, L. H. F, IV: 3
Green, T. F. F, III: 1
Greene, E. B. F, IV: 2
Greene, J. D. F, III: 4
Greene, Sir W. A. FHM, III: 1
Greene, W. C. F, IV: 3
Gregory, H. E. F, II: 1
Gregory, W. K. F, II: 3
Grew, J. C. F, III: 2
Grinnell, F. W. F, III: 1
Gulick, C. B. F, IV: 3
Guy, H. FHM, IV: 4
Haberler, G. F, III: 3
Hack, R. K. F, IV: 3
Hadamard, J. S. FHM, I: 1
Haertlein, A. F, I: 4

Haig, R. M. F, III: 3
Haines, C. G. F, III: 2
Hall, J. L. F, III: 1
Hand, A. N. F, III: 1
Hand, L. F, III: 1
Hardy, A. C. F, I: 2
Hardy, G. H. FHM, I: 1
Harmon, A. M. F, IV: 3
Harno, A. J. F, III: 1
Harper, R. A. F, II: 2
Harriman, H. I. F, III: 4
Harris, L. F, I: 3
Harrison, G. R. F, I: 2
Harrison, R. G. F, II: 4
Hart, A. B. F, III: 2
Hastings, A. B. F, I: 3
Hatch, W. H. P. F, IV: 1
Havens, R. D. F, IV: 3
Hawkins, R. L. F, IV: 3
Hawtrey, R. G. FHM, III: 3
Hayes, H. V. F, I: 2
Hazard, P. FHM, IV: 4
Hazen, C. D. F, IV: 2
Hazen, H. L. F, I: 4
Healy, W. F, IV: 1
Heidel, W. A. F, IV: 1
Heilman, W. C. F, IV: 4
Henderson, L. J. F, I: 3
Hendrickson, G. L. F, IV: 3
Henshaw, S. F, II: 3
Hertzsprung, E. FHM, I: 1
Heyrovsky, J. FHM, I: 3
Hill, A. V. FHM, II: 3
Hill, B. H. F, IV: 2
Hill, E. B. F, IV: 4
Hille, E. F, I: 1
Hillyer, R. S. F, IV: 4
Hindemith, P. FHM, IV: 4
Hisaw, F. L. F, II: 3
Hitchcock, F. L. F, I: 1
Hoadley, L. F, II: 3
Hoagland, H. F, II: 3
Hockett, R. C. F, I: 3
Hocking, W. E. F, IV: 1
Holcombe, A. N. F, III: 2
Holdworth, Sir W. S. FHM, III: 1
Holmes, A. FHM, II: 1
Holmes, E. J. F, III: 4
Holmes, H. W. F, III: 3
Holmes, S. J. F, II: 3
Hooton, E. A. F, IV: 2
Hopkinson, C. F, IV: 4
Horwood, M. P. F, I: 4
Hoskins, H. L. F, IV: 2
Hoskins, R. G. F, II: 3
Hovgaard, W. F, I: 4
Howard, L. O. F, II: 3
Howard, W. G. F, IV: 3
Howe, M. A. DeW. F, IV: 4
Howe, P. R. F, II: 4
Howell, W. H. F, II: 4
Hrdlička, A. F, IV: 2
Hu Shih. FHM, III: 2
Hubbard, J. C. F, I: 2
Hudnut, J. F, IV: 4
Hudson, M. O. F, III: 2
Hughes, C. E. F, III: 1
Hull, C. L. F, IV: 1
Hull, G. F. F, I: 2
Hume, E. E. F, II: 4
Humphreys, W. J. F, II: 1
Hunsaker, J. C. F, I: 4
Hunt, F. V. F, I: 2
Hunt, R. F, II: 4
Hunter, W. S. F, IV: 1
Huntington, A. M. F, IV: 4
Huntington, E. F, II: 1
Huntington, E. V. F, I: 1
Huntress, E. H. F, I: 3
Husserl, E. FHM, IV: 1
Hutchins, C. C. F, I: 2
Hyvernat, E. X. L. H. F, IV: 3
Isaacs, N. F, III: 1
Ives, J. E. F, I: 2
Jack, J. G. F, II: 2
Jack, J. R. F, I: 4
Jackson, C. N. F, IV: 3
Jackson, D. F, I: 1
Jackson, D. C. F, I: 4
Jackson, F. J. F. F, IV: 1
Jackson, H., Jr. F, II: 4
Jackson, R. T. F, II: 1
Jacobi, H. G. FHM, IV: 3
Jaeger, W. W. F, IV: 3
Jaggar, T. A. F, II: 1
James, H. F, IV: 4
James, W. F, IV: 4
Janet, P. FHM, IV: 1
Jellinek, E. M. F, I: 1
Jennings, H. S. F, II: 3
Jennings, W. L. F, I: 3
Jepson, W. L. F, II: 2
Jessup, P. C. F, III: 2
Jewett, F. B. F, I: 4
Jewett, J. R. F, IV: 3
Joffé, A. F. FHM, I: 2
Johnson, D. W. F, II: 1
Johnson, L. J. F, I: 4
Johnson, M. M. F, III: 1
Johnston, I. M. F, II: 2
Jones, D. F. F, II: 2
Jones, G. F, I: 3
Jones, H. M. F, IV: 4
Joslin, E. P. F, II: 4
Keenan, J. H. F, I: 4
Keith, Sir A. FHM, II: 4
Keith, A. F, II: 1
Kelsen, H. FHM, III: 1
Kemble, E. C. F, I: 2
Kemmerer, E. W. F, III: 3
Kendall, H. P. F, III: 4
Keniston, H. F, IV: 3
Kent, N. A. F, I: 2
Kent, R. G. F, IV: 3
Keyes, F. G. F, I: 3
Keynes, J. M. FHM, III: 3
Kistiakowsky, G. B. F, I: 3
Kittredge, G. L. F, IV: 3
Knight, F. H. F, III: 3
Knudson, A. C. F, IV: 1
Köhler, W. FHM, IV: 1
Koffka, K. F, IV: 1
Kofoid, C. A. F, II: 3
Koussevitzky, S. FHM, IV: 4
Kraus, C. A. F, I: 3
Kretschmer, P. FHM, IV: 3
Kroeber, A. L. F, IV: 2
Krogh, A. FHM, II: 3
Kurath, H. F, IV: 3
Lake, K. F, IV: 2
Lamb, A. B. F, I: 3
Lamont, T. W. F, III: 4
Lampland, C. O. F, I: 1
Lancaster, H. C. F, IV: 3
Landis, J. M. F, III: 1
Lane, A. C. F, II: 1
Langley, E. F. F, IV: 3
Langmuir, I. F, I: 3
Lanman, C. R. F, IV: 3
La Piana, G. F, IV: 2
Lapicque, L. E. FHM, II: 3
Larmor, Sir J. FHM, I: 2
Larsen, E. S. F, II: 1
Lashley, K. S. F, IV: 1
Lawrence, E. O. F, I: 2
Lawrence, R. R. F, I: 4
Lawrence, W. F, IV: 1
Lawrence, W. H. F, I: 4
Lawson, A. C. F, II: 1
Lawton, F. F, III: 1
Lee, R. I. F, II: 4
Leeds, M. E. F, III: 4
Lefavour, H. F, I: 2
Leith, C. K. F, II: 1
Leland, W. G. F, IV: 2
Lessells, J. M. F, I: 4
Levi-Civita, T. FHM, I: 1
Lewis, C. I. F, IV: 1
Lewis, F. T. F, II: 3
Lewis, G. N. F, I: 3
Lewis, L. R. F, IV: 4
Lewis, W. K. F, I: 3
Lillie, F. R. F, II: 3
Lillie, R. S. F, II: 3
Lindsay, R. B. F, I: 2
Linforth, I. M. F, IV: 3
Little, C. C. F, III: 4
Livingston, B. E. F, II: 2
Locke, E. A. F, II: 4
Lodge, J. E. F, IV: 4

Lombardi, L. FHM, I: 4
Longcope, W. T. F, II: 4
Lowell, A. L. F, III: 2
Lowes, J. L. F, IV: 4
Lull, R. S. F, II: 3
Lund, F. B. F, II: 4
Luyten, W. J. F, I: 1
Lyman, T. F, I: 2
McAdie, A. G. F, II: 1
McCollester, L. S. F, IV: 1
McCrea, R. C. F, III: 3
McEwen, G. F. F, II: 1
McIlwain, C. H. F, IV: 2
MacInnes, D. A. F, I: 3
MacIver, R. M. F, III: 3
McKeehan, L. W. F, I: 2
McLaren, W. W. F, III: 3
McLaughlin, D. H. F, II: 1
Macmillan, Lord. FHM, III: 1
McNair, M. P. F, III: 3
Macneil, S. F, III: 1
MacNider, W. de B. F, II: 4
Maginnis, C. D. F, IV: 4
Magruder, C. F, III: 1
Main, C. T. F, I: 4
Makarewicz, J. FHM, III: 1
Mallory, F. B. F, II: 4
Malone, D. F, III: 4
Mangelsdorf, P. C. F, II: 2
Manship, P. F, IV: 4
Margerie, E. de. FHM, II: 1
Mark, E. L. F, II: 3
Mark, K. L. F, I: 3
Marks, L. S. F, I: 4
Marshall, L. C. F, III: 3
Mason, D. G. F, IV: 4
Mason, E. S. F, III: 3
Mather, F. J. F, IV: 4
Mather, K. F. F, II: 1
Mathews, E. B. F, II: 1
Matthews, A. F, IV: 3
Maunier, R. FHM, III: 3
May, J. V. F, III: 4
Mayo, E. F, III: 3
Mazon, P. FHM, IV: 3
Mead, A. D. F, II: 3
Mead, W. J. F, II: 1
Meinecke, F. FHM, IV: 2
Melander, A. L. F, II: 3
Menzel, D. H. F, I: 1
Meriam, R. S. F, III: 3
Meritt, B. D. F, IV: 3
Merriam, C. E. F, III: 2
Merriam, J. C. F, II: 1
Merrill, E. D. F, II: 2
Merriman, R. B. F, IV: 2
Merritt, E. G. F, I: 2
Meyer, K. F. F, II: 3
Milas, N. A. F, I: 3
Miller, D. C. F, I: 2
Miller, G. A. F, I: 1
Miller, G. S. F, II: 3
Miller, J. A. F, I: 1
Miller, W. J. F, II: 1
Millikan, R. A. F, I: 2
Millis, H. A. F, III: 3
Mills, F. C. F, III: 3
Mimno, H. R. F, I: 2
Miner, L. M. S. F, II: 4
Minot, G. R. F, II: 4
Mitchell, S. F, IV: 2
Mitchell, S. A. F, I: 1
Mitchell, W. C. F, III: 3
Mitchell, W. DeW. F, III: 1
Miyabe, K. FHM, II: 2
Miyajima, M. FHM, II: 4
Molengraaff, G. A. F. FHM, II: 1
Monroe, A. E. F, III: 3
Moore, E. C. F, IV: 1
Moore, J. B. F, III: 2
Moreland, E. L. F, I: 4
Morgan, E. M. F, III: 1
Morgan, T. H. F, II: 3
Morison, S. E. F, IV: 2
Morris, F. K. F, II: 1
Morse, M. F, I: 1
Morse, P. M. F, I: 2
Morton, A. A. F, I: 3
Moss, W. L. F, II: 4
Moulton, F. R. F, I: 1
Moulton, H. G. F, III: 3
Mueller, E. F, I: 3
Müller, F. von. FHM, II: 4
Mueller, J. H. F, II: 4
Munro, W. B. F, III: 2
Murdock, K. B. F, IV: 4
Murray, G. FHM, IV: 4
Murray, H. A., Jr. F, IV: 1
Neilson, W. A. F, IV: 4
Newhouse, W. H. F, II: 1
Nitze, W. A. F, IV: 3
Nock, A. D. F, IV: 1
Norris, J. F. F, I: 3
Nourse, E. G. F, III: 3
Noyes, G. R. F, IV: 3
Noyes, W. A. F, I: 3
Noyes, W. A., Jr. F, I: 3
O'Connell, W. H. F, IV: 1
O'Connor, J. F, IV: 1
Oertel, H. FHM, IV: 3
Ogburn, W. F. F, III: 3
Oldenberg, O. F, I: 2
Oldfather, W. A. F, IV: 3
Olmsted, F. L. F, I: 4
Osgood, R. B. F, II: 4
Osterhout, W. J. V. F, II: 2
Page, C. H. F, IV: 4
Page, L. F, I: 2
Palmer, W. W. F, II: 4
Paneth, F. FHM, I: 3
Park, C. E. F, IV: 1
Park, C. F. F, I: 4
Park, R. E. F, III: 3
Parker, G. H. F, II: 3
Parkman, H., Jr. F, III: 1
Paschen, F. FHM, I: 2
Patch, H. R. F, IV: 3
Patterson, R. P. F, III: 1
Pearl, R. F, II: 3
Pearse, L. F, I: 4
Pease, A. S. F, IV: 3
Peers, E. A. FHM, IV: 4
Peirce, G. J. F, II: 2
Pender, H. F, I: 4
Pepper, G. W. F, III: 1
Pfeiffer, R. H. F, IV: 2
Phelps, W. L. F, IV: 4
Phillips, H. B. F, I: 1
Philpott, A. J. F, IV: 4
Picard, C. E. FHM, I: 1
Pickard, G. W. F, I: 4
Pidal, R. M. FHM, IV: 3
Pierce, G. W. F, I: 2
Piéron, H. FHM, IV: 1
Pigou, A. C. FHM, III: 3
Pilsbry, H. A. F, II: 3
Pincus, G. F, II: 3
Planck, M. FHM, I: 2
Poor, C. L. F, I: 1
Post, C. R. F, IV: 4
Pound, R. F, III: 1
Prandtl, L. FHM, I: 4
Pratt, C. C. F, IV: 1
Pratt, F. H. F, II: 3
Pratt, J. H. F, II: 4
Prescott, H. W. F, IV: 3
Prescott, S. C. F, I: 3
Prest, W. M. F, III: 1
Probst, E. FHM, I: 4
Purves, C. B. F, I: 2
Putnam, H. F, III: 4
Putnam, T. J. F, II: 4
Qua, S. E. F, III: 1
Quinby, W. C. F, II: 4
Rabaud, H. FHM, IV: 4
Rand, E. K. F, IV: 3
Rand, H. W. F, II: 3
Rapport, D. F, II: 3
Raymond, P. E. F, II: 1
Redfield, A. C. F, II: 3
Regan, C. T. FHM, II: 3
Rehder, A. F, II: 2
Reisner, G. A. F, IV: 2
Renner, O. FHM, II: 2
Richards, A. N. F, II: 3
Richards, R. H. F, I: 3
Richardson, R. G. D. F, I: 1
Riddle, O. F, II: 3
Ripley, A. L. F, III: 4
Rist, C. FHM, III: 3

Ritter, W. E. F, II: 3
Robinson, D. M. F, IV: 2
Robinson, F. N. F, IV: 3
Rogers, A. F. F, II: 1
Rollins, H. E. F, IV: 3
Romer, A. S. F, II: 3
Root, R. K. F, IV: 3
Rosanoff, M. A. F, I: 3
Rosenblueth, A. F, II: 4
Rossby, C. G. A. F, II: 1
Rostovtzeff, M. I. F, IV: 2
Rowe, L. S. F, III: 3
Rowntree, B. S. FHM, III: 4
Ruggles, A. H. F, II: 4
Ruggles, O. C. F, III: 3
Russell, F. F. F, II: 4
Russell, G. E. F, I: 4
Russell, H. N. F, I: 1
Ruthven, A. G. F, II: 3
Rutledge, G. F, I: 1
Ruzicka, L. FHM, I: 3
Ryan, J. H. F, IV: 1
Sachs, P. J. F, IV: 4
Salter, W. T. F, II: 4
Sanders, H. A. F, IV: 3
Sanders, T. H. F, III: 3
Sarton, G. F, IV: 2
Saunders, F. A. F, I: 2
Sax, K. F, II: 2
Sayles, R. W. F, II: 1
Sayre, F. B. F, III: 1
Scatchard, G. F, I: 3
Schaller, W. T. F, II: 1
Schell, E. H. F, III: 4
Schevill, R. F, IV: 3
Schlesinger, F. F, I: 1
Schmitt, B. E. F, IV: 2
Schuchert, C. F, II: 1
Schumb, W. C. F, I: 3
Schumpeter, J. A. F, III: 3
Scott, A. W. F, III: 1
Scott, D. F, IV: 2
Scott, J. B. F, III: 1
Scott, W. B. F, II: 1
Sedgwick, E. F, IV: 4
Sedgwick, H. D. F, IV: 4
Sellards, A. W. F, II: 4
Setchell, W. A. F, II: 2
Seward, Sir A. C. FHM, II: 2
Seymour, C. F, III: 4
Shapley, H. F, I: 1
Shattuck, G. C. F, II: 4
Shattuck, H. L. F, III: 4
Shaw, H. S. F, III: 4
Shaw, Sir W. N. FHM, II: 1
Shear, T. L. F, IV: 2
Sherrill, H. K. F, IV: 1
Sherrill, M. S. F, I: 3
Sherrington, Sir C. S. FHM, II: 4
Shimer, H. W. F, II: 1
Sidgwick, N. V. FHM, I: 3
Simpson, S. P. F, III: 1
Sinnott, E. W. F, II: 2
Slater, J. C. F, I: 2
Slipher, V. M. F, I: 1
Slocum, F. F, I: 1
Smith, D. S. F, IV: 4
Smith, G. M. F, II: 2
Smith, H. E. F, IV: 3
Smith, H. M. F, I: 3
Smith, L. B. F, I: 3
Smith, P. F, III: 4
Smith, Sir W. W. FHM, II: 2
Smyth, H. L. F, I: 4
Snyder, C. F, III: 3
Snyder, V. F, I: 1
Soderberg, R. C. F, I: 4
Sollmann, T. H. F, II: 4
Sombart, W. FHM, III: 3
Sorokin, P. A. F, III: 3
Spalding, W. R. F, IV: 4
Spemann, H. FHM, II: 3
Sperry, W. L. F, IV: 1
Spinden, H. J. F, IV: 2
Spofford, C. M. F, I: 4
Sprague, O. M. W. F, III: 3
Stafford, R. H. F, IV: 1
Stakman, E. C. F, II: 2
Stammler, R. FHM, II: 1
Stamp, Baron. FHM, III: 4
Sterns, A. W. F, III: 4
Stebbins, J. F, I: 1
Stein, Sir A. FHM, IV: 2
Steinmetz, S. R. FHM, III: 3
Stetson, H. T. F, I: 1
Stevens, J. F. F, I: 4
Stewart, G. W. F, I: 2
Stiles, C. W. F, II: 4
Stodola, A. FHM, I: 4
Stone, H. F. F, III: 1
Stone, J. S. F, I: 2
Stone, M. H. F, I: 1
Strawinsky, I. FHM, IV: 4
Street, J. C. F, I: 2
Strong, R. P. F, II: 4
Struik, D. J. F, I: 1
Struve, P. B. FHM, III: 3
Sturtevant, E. H. F, IV: 3
Swan, T. W. F, III: 1
Takayanagi, K. FHM, III: 1
Talbot, F. B. F, II: 4
Tamarkin, J. D. F, I: 1
Tatlock, J. S. P. F, IV: 3
Taussig, F. W. F, III: 3
Taylor, C. H. F, III: 4
Taylor, C. H. F, IV: 2
Taylor, F. H. F, IV: 4
Teggart, F. J. F, III: 3
Terman, L. M. F, IV: 1
Thimann, K. V. F, II: 2
Thomas, F. W. FHM, IV: 3
Thomas, W. I. F, III: 3
Thompson, Sir D'A. W. FHM, II: 3
Thompson, M. deK. F, I: 2
Thomson, Sir J. J. FHM, I: 2
Thomson, W. F, IV: 3
Thorndike, E. L. F, IV: 1
Thurston, E. S. F, III: 1
Thurstone, L. L. F, IV:1
Tolman, R. C. F, I: 3
Torrey, C. C. F, IV: 3
Tosdal, H. R. F, III: 3
Tozzer, A. M. F, IV: 2
Trelease, W. F, II: 2
Trevelyan, G. M. FHM, IV: 2
Tucker, D. S. F, III: 3
Turner, C. E. F, III: 4
Tyzzer, E. E. F, II: 4
Urey, H. C. F, I: 3
Usher, A. P. F, III: 3
Vallarta, M. S. F, I: 2
Vallée Poussin, C. J. de la. FHM, I: 1
Van de Graaff, R. J. F, I: 2
Van Slyke, D. D. F, II: 4
Van Vleck, J. H. F, I: 2
Vaughan, T. W. F, II: 1
Veblen, O. F, I: 1
Vecchio, G. Del. FHM, III: 1
Verhoeff, F. H. F, II: 4
Viets, H. R. F, IV: 2
Vincent, J. H. FHM, II: 4
Viner, J. F, III: 3
Wagner, K. W. FHM, I: 4
Walsh, J. L. F, I: 1
Wambaugh, E. F, III: 1
Warner, E. P. F, I: 4
Warren, B. E. F, I: 2
Warren, B. W. F, III: 1
Warren, C. H. F, II: 1
Warren, J. F, III: 1
Washburn, H. B. F, IV: 1
Watson, J. B. F, IV: 1
Wearn, J. T. F, II: 4
Weatherby, C. A. F, II: 2
Webster, D. L. F, I: 2
Webster, E. S. F, III: 4
Weiss, S. F, II: 4
Wells, F. L. F, IV: 1
Westergaard, H. M. F, I: 4
Weston, G. B. F, IV: 3
Weston, K. E. F, IV: 4
Weston, R. S. F, I: 4
Weston, W. H., Jr. F, II: 2
Wetmore, R. H. F, II: 2
Weyl, H. FHM, I: 1
Weysse, A. W. F, II: 3
White, P. D. F, II: 4
Whitehead, A. N. F, I: 1
Whitehead, T. N. F, III: 3
Whitlock, H. P. F, II: 1

Whitman, E. A. F, III: 1
Whitmore, F. C. F, I: 3
Whitney, W. R. F, I: 3
Whittlesey, D. S. F, II: 1
Widder, D. V. F, I: 1
Wieland, H. FHM, I: 3
Wilkins, E. H. F, IV: 3
Williams, J. H. F, III: 3
Williams, R. S. F, I: 3
Willis, B. F, II: 1
Willits, J. H. F, III: 3
Willoughy, W. F. F, III: 2
Willoughby, W. W. F, III: 2
Willstätter, R. FHM, I: 3
Wilson, E. B. F, I: 2
Wilson, G. G. F, III: 2
Winthrop, G. L. F, IV: 4
Wislocke, G. B. F, II: 3
Wissler, C. F, IV: 2
Wolbach, S. B. F, II: 4
Wolfson, H. A. F, IV: 3
Wolman, L. F, III: 3
Wood, R. W. F, I: 2
Woodworth, R. S. F, IV: 1
Worcester, J. R. F, I: 4
Worrall, D. E. F, I: 3
Worrell, W. H. F, IV: 3
Wright, Lord. FHM, III: 1
Wright, C. H. C. F, IV: 4
Wright, F. E. F, II: 1
Wright, Q. F, III: 2
Wu, J. C. H. FHM, III: 1
Wyman, J., Jr. F, II: 3
Yeomans, H. A. F, III: 2
Yerkes, R. M. F, IV: 1
Young, B. L. F, III: 4
Young, K. F, IV: 3
Young, O. D. F, III: 4
Zeleny, J. F, I: 2
Zimmerman, C. C. F, III: 3

STATUTES AND STANDING VOTES.

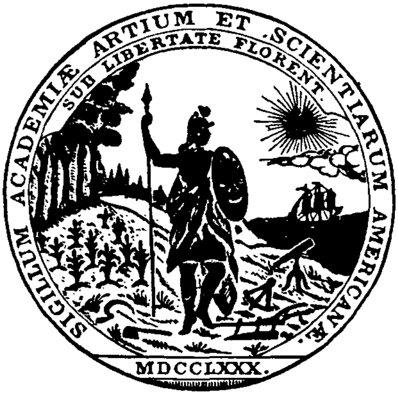
STATUTES.

Adopted November 8, 1911: *amended May* 8, 1912, *January* 8, *and May* 14, 1913, *April* 14, 1915, *April* 12, 1916, *April* 10, 1918, *May* 14, 1919, *February* 8, *April* 12, *and December* 13, 1922, *February* 14, *March* 14, *and October* 10, 1923, *March* 10, 1926, *May* 9, 1928, *April* 8 *and November* 11, 1931, *April* 12, 1933, *February* 14, 1934, *December* 14, 1938, *January* 11, *April* 12, 1939 *and May* 8, 1940.

CHAPTER I.

The Corporate Seal.

Article 1. The Corporate Seal of the Academy shall be as here depicted:


SIGILLUM ACADEMIÆ ARTIUM ET SCIENTIARUM AMERICANÆ
SUB LIBERTATE FLORENT
MDCCLXXX.

Article 2. The Recording Secretary shall have the custody of the Corporate Seal.

See Chap. v, art. 3; chap. vi, art. 2.

CHAPTER II.

Fellows and Foreign Honorary Members and Dues.

Article 1. The Academy consists of Fellows, who are either citizens or residents of the United States of America, and Foreign Honorary Members. They are arranged in four Classes, according to the Arts and Sciences in which they are severally proficient, and each Class is divided into four Sections, namely:

Class I. *The Mathematical and Physical Sciences*

Section 1. Mathematics and Astronomy
Section 2. Physics
Section 3. Chemistry
Section 4. Technology and Engineering

Class II. *The Natural and Physiological Sciences*

Section 1. Geology, Mineralogy, and Physics of the Globe
Section 2. Botany
Section 3. Zoölogy and Physiology
Section 4. Medicine and Surgery

Class III. *The Social Arts*

Section 1. Jurisprudence
Section 2. Government, International Law, and Diplomacy
Section 3. Economics and Sociology
Section 4. Administration and Affairs

Class IV. *The Humanities*

Section 1. Theology, Philosophy, and Psychology
Section 2. History, Archæology, and Anthropology
Section 3. Philology
Section 4. The Fine Arts and Belles Lettres

Article 2. The number of Fellows shall not exceed Eight hundred, of whom not more than Six hundred shall be residents of Massachusetts, nor shall there be more than Two hundred and twenty in any one Class.

ARTICLE 3. The number of Foreign Honorary Members shall not exceed One hundred and thirty. They shall be chosen from among citizens of foreign countries most eminent for their discoveries and attainments in any of the Classes above enumerated. There shall not be more than Thirty-five in any one Class.

ARTICLE 4. If any person, after being notified of his election as Fellow, shall neglect for six months to accept in writing, or, if a Fellow resident within fifty miles of Boston shall neglect to pay his Admission Fee, his election shall be void; and if any Fellow resident within fifty miles of Boston shall neglect to pay his Annual Dues for six months after they are due, provided his attention shall have been called to this Article of the Statutes in the meantime, he shall cease to be a Fellow; but the Council may suspend the provisions of this Article for a reasonable time

With the previous consent of the Council, the Treasurer may dispense (*sub silentio*) with the payment of the Admission Fee or of the Annual Dues or both whenever he shall deem it advisable. In the case of officers of the Army or Navy who are out of the Commonwealth on duty, payment of the Annual Dues may be waived during such absence if continued during the whole financial year and if notification of such expected absence be sent to the Treasurer. Upon similar notification to the Treasurer, similar exemption may be accorded to Fellows subject to Annual Dues, who may temporarily remove their residence for at least two years to a place more than fifty miles from Boston.

If any person elected a Foreign Honorary Member shall neglect for six months after being notified of his election to accept in writing, his election shall be void.

See Chap. vii, art. 2.

ARTICLE 5. Every Fellow resident within fifty miles of Boston hereafter elected shall pay an Admission Fee of Ten dollars, unless previously as an Associate he has paid an Admission Fee of like amount.

Every Fellow resident within fifty miles of Boston shall, and others may, pay such Annual Dues, not exceeding Fifteen dollars, as shall be voted by the Academy at each Annual Meeting, when they shall become due; but any Fellow shall be exempt from the annual payment if, at any time after his admission, he shall pay into the treasury Two hundred dollars in addition to his previous payments. Any Fellow shall also be exempt from Annual Dues who has paid such dues for forty years, or, having attained the age of seventy-five has paid dues for twenty-five years.

Fellows residing more than fifty miles from Boston elected after 1938 shall, and other non-resident Fellows may, pay annual dues of five dollars, which shall entitle them to all privileges of resident Fellows.

All Commutations of the Annual Dues shall be and remain permanently funded, the interest only to be used for current expenses.

Any Fellow not previously subject to Annual Dues who takes up his residence within fifty miles of Boston, shall pay to the treasurer within three months thereafter Annual Dues for the current year, failing which his Fellowship shall cease; but the Council may suspend the provisions of this Article for a reasonable time.

Only Fellows who pay Annual Dues or have commuted them may hold office in the Academy or serve on the Standing Committees or vote at meetings.

ARTICLE 6. Fellows who pay or have commuted the Annual Dues and Foreign Honorary Members shall be entitled to receive gratis one copy of all numbers of the Proceedings and Memoirs of the Academy which have been issued after their election.

See Chap. xi, art. 2.

ARTICLE 7. Diplomas signed by the President and the Vice-President of the Class to which the member belongs, and countersigned by the Secretaries, shall be given to Foreign Honorary Members and to Fellows.

ARTICLE 8. If, in the opinion of a majority of the entire Council, any Fellow or Foreign

Honorary Member shall have rendered himself unworthy of a place in the Academy, the Council shall recommend to the Academy the termination of his membership; and if three-fourths of the Fellows present, out of a total attendance of not less than fifty at a Stated Meeting, or at a Special Meeting called for the purpose, shall adopt this recommendation, his name shall be stricken from the Roll.

See Chap. iii; chap. vi, art. 1; chap. x, art. 1; chap. xi, art. 2.

CHAPTER III.

ELECTION OF FELLOWS AND FOREIGN HONORARY MEMBERS.

The procedure in the election of Fellows and Foreign Honorary Members shall be as follows:

Nominations to Fellowship or Foreign Honorary Membership in any Section must be signed by two Fellows of that Section, or by three Fellows of any Section, and sent to the Corresponding Secretary accompanied by a statement of the qualifications of the nominee and brief biographical data.

Notice shall be sent to every Fellow not later than the fifteenth of January in each year, reminding him that all nominations must be in the hands of the Corresponding Secretary before the first of February following. The Corresponding Secretary shall, on the second of February, transmit to the several Vice-Presidents the nominations for Fellows and Foreign Honorary Members in their respective classes. Each Class Committee shall, before the sixteenth of February, consider the nominations, and may add others for the purpose of securing proper membership in the Academy, to the end that those in the country of highest distinction in their several classes may be Fellows.

A list of the nominees, giving a brief account of each, with the names of the nominators, shall be sent to every Fellow with a request that he return the list with such confidential comments and indications of preference as he may choose to make.

All the nominations, with any comments thereon and with expressions of preference on the part of the Fellows, shall be referred to the appropriate Class Committees, which shall canvass them, and report their recommendations in writing to the Council before the Stated Meeting of the Academy in April.

Elections of Fellows and Foreign Honorary Members shall be made by the Council before the Annual Meeting in May, and announced at that meeting.

Persons nominated in any year, but not elected, may be carried over to the list of nominees for the next year at the discretion of the Council, but shall not be further continued unless renominated.

See Chap. ii; chap. vi, art. 1; chap. x, art. 1.

CHAPTER IV.

OFFICERS.

ARTICLE 1. The Officers of the Academy shall be a President (who shall be Chairman of the Council), four Vice-Presidents (one from each Class), a Corresponding Secretary (who shall be Secretary of the Council), a Recording Secretary, a Treasurer, a Librarian, and an Editor, all of whom shall be elected by ballot at the Annual Meeting, and shall hold their respective offices for one year, and until others are duly chosen and installed.

There shall be also sixteen Councillors, one from each Section of each Class. At each Annual Meeting four Councillors, one from each Class, shall be elected by ballot to serve for the full term of four years and until others are duly chosen and installed. The same Fellows shall not be eligible for two successive terms.

The Councillors, with the officers previously named, and the Chairmen of the House Committee and the Committee on Resources and Policy, *ex officiis,* shall constitute the Council.

See Chap. xi, art. 1.

ARTICLE 2. If any officer be unable, through death, absence, or disability, to fulfill the duties of his office, or if he shall resign, his place may be filled by the Council in its discretion for any part or the whole of the unexpired term.

ARTICLE 3. At the Stated Meeting in March, the President shall appoint a Nominating Committee of four Fellows having the right to vote, one from each Class. This Committee shall prepare a list of nominees for the several offices to be filled, and for the Standing Committees, and file it with the Recording Secretary not later than four weeks before the Annual Meeting.

See Chap. vi, art. 2.

ARTICLE 4. Independent nominations for any office, if signed by at least twenty Fellows having the right to vote, and received by the Recording Secretary not less than ten days before the Annual Meeting, shall be inserted in the call therefor, and shall be mailed to all the Fellows having the right to vote.

See Chap. vi, art. 2.

ARTICLE 5. The Recording Secretary shall prepare for use in voting at the Annual Meeting a ballot containing the names of all persons duly nominated for office.

CHAPTER V.

THE PRESIDENT.

ARTICLE 1. The President, or in his absence the senior Vice-President present (seniority to be determined by length of continuous Fellowship in the Academy), shall preside at all meetings of the Academy. In the absence of all these officers, a Chairman of the meeting shall be chosen by ballot.

ARTICLE 2. Unless otherwise ordered, all Committees which are not elected by ballot shall be appointed by the presiding officer.

ARTICLE 3. Any deed or writing to which the Corporate Seal is to be affixed, except leases of real estate, shall be executed in the name of the Academy by the President or, in the event of his death, absence, or inability, by one of the Vice-Presidents, when thereto duly authorized.

See Chap. ii, art. 7; chap. iv, art. 1, 3; chap. vi, art. 2; chap. vii, art. 1; chap. x, art. 6; chap. xi, art. 1, 2; chap. xii, art. 1.

CHAPTER VI.

THE SECRETARIES.

ARTICLE 1. The Corresponding Secretary shall conduct the correspondence of the Academy and of the Council, recording or making an entry of all letters written in its name, and preserving for the files all official papers which may be received. At each meeting of the Council he shall present the communications addressed to the Academy which have been received since the previous meeting, and at the next meeting of the Academy he shall present such as the Council may determine.

He shall notify all persons who may be elected Fellows or Foreign Honorary Members, send to each a copy of the Statutes, and on their acceptance issue the proper Diploma. He shall also notify all meetings of the Council; and in case of the death, absence, or inability of the Recording Secretary he shall notify all meetings of the Academy.

Under the direction of the Council, he shall keep a List of the Fellows and Foreign Honorary Members, arranged in their several Classes and Sections. It shall be printed annually and issued as of the first day of July.

See Chap. ii, art. 7; chap. iii; chap. iv, art. 1; chap. x, art. 6; chap. xi, art. 1; chap. xii, art. 1.

ARTICLE 2. The Recording Secretary shall have the custody of the Charter, Corporate Seal, Archives, Statute-Book, Journals, and all literary papers belonging to the Academy.

Fellows borrowing such papers or documents shall receipt for them to their custodian.

The Recording Secretary shall attend the meetings of the Academy and keep a faithful record of the proceedings with the names of the Fellows present; and after each meeting is duly opened, he shall read the record of the preceding meeting.

He shall notify the meetings of the Academy to each Fellow and by mail at least seven days beforehand, and in his discretion may also cause the meetings to be advertised; he shall apprise Officers and Committees of their election or appointment, and inform the Treasurer of appropriations of money voted by the Academy.

After all elections, he shall insert in the Records the names of the Fellows by whom the successful nominees were proposed.

He shall send the Report of the Nominating Committee in print to every Fellow having the right to vote at least three weeks before the Annual Meeting.

See Chap. iv, art. 3.

In the absence of the President and of the Vice-President he shall, if present, call the meeting to order, and preside until a Chairman is chosen.

See Chap. i; chap. ii, art. 7; chap. iv, art. 3, 4, 5; chap. x, art. 6; chap. xi, art. 1, 2; chap. xii, art. 1, 3.

ARTICLE 3. The Secretaries, with the Editor, shall have authority to publish such of the records of the meetings of the Academy as may seem to them likely to promote its interests.

CHAPTER VII.

THE TREASURER AND THE TREASURY.

ARTICLE 1. The Treasurer shall collect all money due or payable to the Academy and all gifts or bequests made to it. He shall pay all bills due and payable by the Academy when approved by the proper officers. He shall sign all leases of real estate in the name of the Academy. He shall be the official custodian of all bonds, stocks and other securities and, with the written approval of any one member of the Committee on Finance, he shall have full authority to sell and transfer, invest and reinvest from time to time in such manner and upon such terms as shall to him seem best, the whole or any part of the personal property of the said Academy.

He shall keep a faithful account of all receipts and expenditures, submit his acounts annually to the Auditing Committee, and render them at the expiration of his term of office, or whenever required to do so by the Academy or the Council.

He shall keep separate accounts of the income of the Rumford Fund, and of all other special Funds, and of the Appropriation thereof, and render them annually.

His accounts shall always be open to the inspection of the Council.

ARTICLE 2. He shall report annually to the Council at its March meeting on the expected income of the various Funds and from all other sources during the ensuing financial year. He shall also report the names of all Fellows who may be then delinquent in the payment of their Annual Dues.

ARTICLE 3. He shall give such security for the trust reposed in him as the Academy may require.

ARTICLE 4. With the approval of a majority of the Committee on Finance, he may appoint an Assistant Treasurer to perform his duties, for whose acts, as such assistant, he shall be responsible; or, with like approval and responsibility, he may employ any Trust Company doing business in Boston as his agent for the same purpose, the compensation of such Assistant Treasurer or agent to be fixed by the Committee on Finance and paid from the Funds of the Academy.

ARTICLE 5. At the Annual Meeting he shall report in print all his official doings for the preceding year, stating the amount and condition of all the property of the Academy entrusted to him, and the character of the investments.

ARTICLE 6. The Financial Year of the Academy shall begin with the first day of April.

ARTICLE 7. No person or committee shall incur any debt or liability in the name of the Academy, unless in accordance with a previous vote and appropriation therefor by the Academy or the Council, or sell or otherwise dispose of any property of the Academy, except cash or invested funds, without previous consent and approval of the Council.

See Chap. ii, art. 4, 5; chap. vi, art. 2; chap. x, art. 6; chap. xi, art. 1, 2, 3; chap. xii, art. 1.

CHAPTER VIII.

THE LIBRARIAN AND THE LIBRARY.

ARTICLE 1. The Librarian shall have charge of the printed books, keep a correct catalogue thereof, and provide for their delivery from the Library.

At the Annual Meeting, as Chairman of the Committee on the Library, he shall make a Report on its condition.

ARTICLE 2. In conjunction with the Committee on the Library he shall have authority to expend such sums as may be appropriated by the Academy for the purchase of books, periodicals, etc., and for defraying other necessary expenses connected with the Library.

ARTICLE 3. All books procured from the income of the Rumford Fund or of other special Funds shall contain a book-plate expressing the fact.

ARTICLE 4. Books taken from the Library shall be receipted for to the Librarian or his assistant.

ARTICLE 5. Books shall be returned in good order, regard being had to necessary wear with good usage. If any book shall be lost or injured, the Fellow to whom it stands charged shall replace it by a new volume or by a new set, if it belongs to a set, or pay the current price thereof to the Librarian, whereupon the remainder of the set, if any, shall be delivered to the Fellow so paying, unless such remainder be valuable by reason of association.

ARTICLE 6. All books shall be returned to the Library for examination at least one week before the Annual Meeting.

ARTICLE 7. The Librarian shall have the custody of the Publications of the Academy. With the advice and consent of the President, he may effect exchanges with other associations.

See Chap. ii, art. 6; chap. xi, art. 1, 2.

CHAPTER IX.

THE EDITOR AND THE PUBLICATIONS.

ARTICLE 1. The Editor shall have charge of the conduct through the press of the Proceedings and the Memoirs, and all correspondence relative thereto, and shall have power to fix the price at which individual numbers of the Proceedings and Memoirs are sold.

The Editor shall select as Associate Editor one member of the Committee of Publication, and the Associate Editor shall assist the Editor in the duties of his office in such way as the two shall find most convenient.

ARTICLE 2. In conjunction with the Committee of Publication, the Editor shall have authority to expend such sums as may be appropriated by the Academy for printing the publications and for defraying other expenses therewith connected.

ARTICLE 3. All publications which are financed in whole or in part from the income of the Rumford Fund or from the income of other special funds, and all publications of work done with the aid of the Rumford Fund or other special funds, shall contain a conspicuous statement of this fact.

ARTICLE 4. Two hundred extra copies of each paper printed in the Proceedings or Memoirs shall be placed at the disposal of the author without charge.

If, on account of the number of communications offered for publication, it shall be necessary to decline for publication communications otherwise acceptable, members of the Academy shall be given preference in each of the several Classes over non-members; but whenever it shall be necessary to exercise this preference, the Editor shall inform the Council of the fact.

See Chap. iv, art. 1; chap. vi, art. 3; chap. x, art. 6; chap. xi, art. 2, sect. 5.

CHAPTER X.

THE COUNCIL.

ARTICLE 1. The Council shall exercise a discreet supervision over all nominations and elections to membership, and in general supervise all the affairs of the Academy not explicitly reserved to the Academy as a whole or entrusted by it or by the Statutes to standing or special committees.

It shall consider all nominations duly sent to it by any Class Committee, and act upon them in accordance with the provisions of Chapter III.

With the consent of the Fellow interested, it shall have power to make transfers between the several Sections, reporting its action to the Academy.

See Chap. iii; chap. xi, art. 1.

ARTICLE 2. Nine members shall constitute a quorum.

ARTICLE 3. It shall establish rules and regulations for the transaction of its business, and provide all printed and engraved blanks and books of record.

ARTICLE 4. It shall act upon all resignations of officers, and all resignations and forfeitures of Fellowship; and cause the Statutes to be faithfully executed.

It shall appoint all agents and subordinates not otherwise provided for by the Statutes, prescribe their duties, and fix their compensation. They shall hold their respective positions during the pleasure of the Council.

ARTICLE 5. It may appoint, for terms not exceeding one year, and prescribe the functions of, such committees of its number, or of the Fellows of the Academy, as it may deem expedient, to facilitate the administration of the affairs of the Academy or to promote its interests.

ARTICLE 6. At its March meeting it shall receive reports from the President, the Secretaries, the Treasurer, and the Standing Committees, on the appropriations severally needed for the ensuing financial year. At the same meeting the Treasurer shall report on the expected income of the various Funds and from all other sources during the same year.

A report from the Council shall be submitted to the Academy, for action, at the March meeting, recommending the appropriation which in the opinion of the Council should be made.

On the recommendation of the Council, special appropriations may be made at any Stated Meeting of the Academy, or at a Special Meeting called for the purpose.

See Chap. xi, art. 3.

ARTICLE 7. It shall report at every meeting of the Academy such business as it may deem advisable to present.

See Chap. ii, art. 4, 5, 8; chap. iv, art. 1, 2; chap. vi, art. 1; chap. vii, art. 1; chap. xii, art. 1, 4.

CHAPTER XI.

STANDING COMMITTEES.

ARTICLE 1. The Class Committee of each Class shall consist of the Vice-President, who shall be chairman, and the four Councillors of the Class, together with such other officer or officers annually elected as may belong to the Class. It shall consider nominations to Fellowship in its own Class, and report in writing to the Council such as may receive at a Class Committee Meeting a majority of the votes cast, provided at least three shall have been in the affirmative.

See Chap. iii.

ARTICLE 2. At the Annual Meeting the following Standing Committees shall be elected by ballot to serve for the ensuing year.

(i) *The Committee on Finance,* to consist of four Fellows, who shall have general oversight of the funds and investments of the Academy.

See Chap. iv, art. 3; chap. vii, art. 1, 4; chap. x, art. 6.

(ii) *The Committee on Policy and Resources* to consist of five Fellows and the President, *ex officio,* one of the five elected members to be elected each year to serve for a term of five years, except that the five elected in 1939 shall be elected for terms of one, two, three, four, and five years respectively, the Committee to concern itself with procuring funds for the Academy, to study the activities and needs of the Academy, and to recommend, for the approval of the Council, means by which the functions and purposes of the Academy may best be fulfilled.

(iii) *The Rumford Committee,* to consist of seven Fellows, who shall report to the Academy on all applications and claims for the Rumford Premium. It alone shall authorize the purchase of books, publications and apparatus at the charge of the income from the Rumford Fund, and generally shall see to the proper execution of the trust.

See Chap. iv, art. 3; chap. x, art. 6.

(iv) *The Cyrus Moors Warren Committee,* to consist of seven Fellows, who shall consider all applications for appropriations from the income of the Cyrus Moors Warren Fund, and generally shall see to the proper execution of the trust.

See Chap. iv, art. 3; chap. x, art. 6.

(v) *The Committee of Publication,* to consist of the Editor, *ex officio,* as Chairman, and four other Fellows, one from each Class, to whom all communications submitted to the Academy for publication shall be referred, and to whom the printing of the Proceedings and the Memoirs shall be entrusted.

It shall fix the price at which volumes of the publications shall be sold, but Fellows may be supplied at half price with volumes and with single publications which they are not entitled to receive gratis.

It shall determine when the pressure of material offered for publication makes it necessary to give preference to members of the Academy as compared with non-members, or to give priority to certain members as compared with others, and to what extent this preference or priority shall be applied in each of the four Classes, to the end that a proper balance of the facilities of publication with respect to subject matter and authors may be maintained.

See Chap. iv, art. 3; chap. vi, art. 1, 3; chap. ix; chap. x, art. 6.

(vi) *The Committee on the Library,* to consist of the Librarian, *ex officio,* as Chairman, and four other Fellows, one from each Class, who shall examine the Library and make an annual report on its condition and management.

See Chap. iv, art. 3; chap. viii, art. 1, 2; chap. x, art. 6.

(vii) *The House Committee,* to consist of four Fellows, who shall have charge of all expenses connected with the House, including the general expenses of the Academy not specifically assigned to the care of other Committees or Officers.

See Chap. iv, art. 1, 3; chap. x, art. 6.

(viii) *The Committee on Meetings,* to consist of the President, the Recording Secretary, and four other Fellows, who shall have charge of plans for meetings of the Academy.

See Chap. iv, art. 3; chap. x, art. 6.

(ix) *The Auditing Committee,* to consist of two Fellows, who shall audit the accounts of the Treasurer, with power to employ an expert and to approve his bill.

See Chap. iv, art. 3; chap. vii, art. 1; chap. x, art. 6.

(x) *The Committee on Biographical Notices,* to consist of six Fellows, two to be elected each year, one of them to be a Secretary of the Academy, to see that biographical notices of the Fellows are provided.

After the death of a Fellow or Foreign Honorary Member, it shall appoint a member of the Academy to provide a biographical notice for publication in the Proceedings.

Article 3. The Standing Committees shall report annually to the Council in March on the appropriations severally needed for the ensuing financial year; and all bills incurred on account of these Committees, within the limits of the several appropriations made by the Academy, shall be approved by their respective Chairmen.

In the absence of the Chairman of any Committee, bills may be approved by any member of the Committee whom he shall designate for the purpose.

See Chap. vii, art. 1, 7; chap. x, art. 6.

CHAPTER XII.

MEETINGS, COMMUNICATIONS, AND AMENDMENTS.

ARTICLE 1. There shall be annually eight Stated Meetings of the Academy, namely, on the second Wednesday of October, November, December, January, February, March, April, and May. Only at these meetings, or at adjournments thereof regularly notified, or at Special Meetings called for the purpose, shall appropriations of money be made or amendments of the Statutes or Standing Votes be effected.

The Stated Meeting in May shall be the Annual Meeting of the Corporation.

Special Meetings shall be called by either of the Secretaries at the request of the President, of a Vice-President, of the Council, or of ten Fellows having the right to vote; and notifications thereof shall state the purpose for which the meeting is called.

The Council shall have authority, as occasion may demand, to arrange additional meetings and to cancel any of the Statutory meetings, except that meetings for transacting business shall be held as required by the Statutes.

ARTICLE 2. Twenty-five Fellows having the right to vote shall constitute a quorum for the transaction of business at Stated or Special Meetings. Eighteen Fellows shall be sufficient to constitute a meeting for literary or scientific communications and discussions.

ARTICLE 3. Upon the request of the presiding officer or the Recording Secretary, any motion or resolution offered at any meeting shall be submitted in writing.

ARTICLE 4. No report of any paper presented at a meeting of the Academy shall be published by any Fellow without the consent of the author; and no report shall in any case be published by any Fellow in a newspaper as an account of the proceedings of the Academy without the previous consent and approval of the Council. The Council, in its discretion, by a duly recorded vote, may delegate its authority in this regard to one or more of its members.

ARTICLE 5. Fellows may introduce guests at any of the literary or scientific meetings of the Academy.

ARTICLE 6. The Academy shall not express its judgment on literary or scientific memoirs or performances submitted to it, or included in its Publications.

ARTICLE 7. All proposed Amendments of the Statutes shall be referred to a committee, and on its report, at a subsequent Stated Meeting or at a Special Meeting called for the purpose, two-thirds of the ballots cast, and not less than twenty-five, must be affirmative to effect enactment.

ARTICLE 8. Standing Votes may be passed, amended, or rescinded at a Stated Meeting, or at a Special Meeting called for the purpose, by a vote of two-thirds of the members present. They may be suspended by a unanimous vote.

See Chap. ii, art. 5, 8; chap. iii; chap. iv, art. 3, 4, 5; chap. v. art. 1; chap. vi, art. 1, 2; chap. x, art. 7.

STANDING VOTES

1. Communications of which notice has been given to either of the Secretaries shall take precedence of those not so notified.

2. Fellows may take from the Library six volumes at any one time, and may retain them for three months, and no longer. Upon special application, and for adequate reasons assigned, the Librarian may permit a larger number of volumes, not exceeding twelve, to be drawn from the Library for a limited period.

3. Works published in numbers, when unbound, shall not be taken from the Hall of the Academy without the leave of the Librarian.

4. Communications offered for publication in the Proceedings or Memoirs of the Academy shall not be accepted for publication before the author either himself or through some agent, shall have informed the Committee on Meetings of his readiness to use such time as the Committee may assign him at such meeting as may be convenient both to him and to the Committee, for the purpose of presenting to the Academy a general statement of the nature and significance of the results contained in his communication.

RUMFORD PREMIUM

In conformity with the terms of the gift of Sir Benjamin Thompson, Count Rumford, of a certain Fund to the American Academy of Arts and Sciences, and with a decree of the Supreme Judicial Court of Massachusetts for carrying into effect the general charitable intent and purpose of Count Rumford, as expressed in his letter of gift, the Academy is empowered to make from the income of the Rumford Fund, as it now exists, at any Annual Meeting, an award of a gold and a silver medal, being together of the intrinsic value of three hundred dollars, as a Premium to the author of any important discovery or useful improvement in light or heat, which shall have been made and published by printing, or in any way made known to the public, in any part of the continent of America, or any of the American islands; preference always being given to such discoveries as, in the opinion of the Academy, shall tend most to promote the good of mankind; and, if the Academy sees fit, to add to such medals, as a further Premium for such discovery and improvement, a sum of money not exceeding three hundred dollars.

PERMANENT SCIENCE FUND

By an Agreement and Declaration of Trust dated Sept. 5, 1928, the Boston Safe Deposit and Trust Company agrees to accept and hold gifts made to it as Trustee of the Permanent Science Fund . . . and to pay the income . . . to the American Academy of Arts and Sciences, to be applied to such scientific research "as shall be deemed charitable within the broadest possible construction of that term" . . . in such sciences as Mathematics, Physics, Chemistry, Astronomy, Geology, Geography, Zoology, Botany, Anthropology, Psychology, Sociology and Economy, History and Philology, Engineering, Medicine and Surgery, Agriculture, Manufacture and Commerce, Education and any other science of any nature or description whether or not now known or now recognized as scientific; and may be applied to or through public or private associations, societies or institutions, . . . or to or through one or more individuals.

Disbursements from income are voted by the Council of the Academy upon recommendations from the Committee on the Permanent Science Fund. A brochure comprising the First Decennial Report on the history and activities of this committee and a copy of the Agreement and Declaration of Trust is available on request to the Trustee at 100 Franklin Street, Boston, Mass.

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A REVISION OF THE NEARCTIC HEMEROBIIDAE, BEROTHIDAE, SISYRIDAE, POLYSTOECHOTIDAE AND DILARIDAE (NEUROPTERA)

By F. M. Carpenter

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The insects treated in this revision are among the most typical of the Neuroptera (Planipennia). When the family Hemerobiidae was established by Leach (1815), it included nearly all of the insects now comprising the order. Since the beginning of the present century, however, and subsequent to the publication of Banks' "Revision of the Nearctic Hemerobiidae" (1905b), various genera have been removed from the Hemerobiidae and placed in separate families. The groups thus formed (Berothidae, Sisyridae, Polystoechotidae, Dilaridae) have little in common with the restricted family Hemerobiidae; but in order that the scope of the present revision be kept identical with that of Banks', these families have also been included.

During the course of this revisional study, I have examined somewhat more than eight thousand individuals of the families mentioned. Apart from the specimens in the Museum of Comparative Zoology, nearly all of these have been loaned to me by the following individuals, to whom I am indebted for their cooperation: Mr. E. P. Van Duzee, California Academy of Sciences; Dr. J. McDunnough, Canadian Department of Agriculture; Mr. A. B. Gurney, United States National Museum; Professor Franklin Sherman, Clemson College, South Carolina; Dr. C. S. Brimley, North Carolina Department of Agriculture; Dr. Richard Dow, New England Museum of Natural History; Dr. F. E. Lutz, American Museum of Natural History; Dr. H. H. Ross, Illinois State Natural History Survey; Professor C. E. Mickel, University of Minnesota; Dr. Hugo Rodeck, University of Colorado; Dr. C. B. Philip, Hamilton, Montana; Dr. R. B. Friend, Connecticut Agriculture Experiment Station; Professor C. P. Alexander, Massachusetts State College, Mr. J. N. Knull, Ohio State University; Dr. L. P. Wehrle, University of Arizona; Dr. Hugo Kahl, Carnegie Museum; Mr. J. A. G. Rehn, Academy of Natural Sciences, Philadelphia; Dr. W. T. M. Forbes, Cornell University; and Professor H. B. Hungerford, University of Kansas. I am under special obligation to Professor R. C. Smith, of Kansas State College, for the loan of his extensive private collection of these insects, and for the opportunity of seeing many small collections sent to him for identification during the preparation of this revision. I am deeply grateful to Mr. D. E. Kimmins of the British Museum of Natural History for placing at my disposal the type specimens in the Museum collection, and for making detailed comparisons with McLachlan's types, which were received at the Museum after my visit there in 1938. As on previous occasions I am indebted to Professor Banks for many helpful suggestions and criticisms.

The morphology of the Neuroptera in general and of most of the families occurring in the Nearctic region has been extensively treated by Killington, in his excellent monograph of the British Neuroptera (1936). I have accepted in this revision the terminology and homologies proposed by him for the abdominal structures and most other parts of the body. My interpretation of the wing venation, however, is slightly different. Killington has followed Comstock's conclusions (1918) in his account of the venation of the Neuroptera; but I believe the evidence now available requires us to modify these. Martynov has demonstrated (1928) that in the existing Neuroptera the anterior branch of the media of both fore and hind wings is partially coalesced with the radius or with the stem of the radial sector (Rs), so that what appears to be the last (most proximal) branch of Rs is really part of the media, probably the anterior media of Lameere's terminology (1922). Martynov's views have been substantiated by evidence secured during the past ten years and have been applied by Tillyard (1932) and Carpenter (1935) to several groups of Neuroptera. Since I believe that Martynov's interpretation will eventually be accepted by neuropterists in general, it has been used here. This interpretation, as applied to the Hemerobiidae and related families, may be summarized as follows:

Fore wing: the *basal part of MA*, as it leaves M before coalescing with R1, can be seen in many Hemerobiidae and related families; it is the faint, obliquely transverse vein ("basal cross-vein") which has been used by Banks and others in the taxonomy of certain genera. In some species (e.g. *Hemerobius conjunctus* Fitch, *H. dorsatus* Banks) MA coalesces with R for a very short distance, the basal piece of MA joining R nearly as far distad as the point of separation of MA from R. In other species (e.g. *H. humulinus* Linn.) MA coalesces with R for a greater interval, the basal piece of MA joining R near the base of the wing. In still other species, which apparently represent a more advanced state of this evolution, MA coalesces with R from the very base of the wing, no free part of MA being discernible. In most Hemerobiid genera (apparently all except Hemerobius) there is a transverse vein present between MA and MP, shortly after the furcation of MP. It is my conviction that this is a true cross-vein and not the basal part of MA, because in several such species the latter is often visible at the very base of the wing. In certain genera of Hemerobiidae and related families the proximal branch of Rs has apparently migrated basally and has also become partially fused with MA; this is the case in some species (and some specimens of all species) of Sympherobius, Megalomus, Sisyra, Psectra, etc.

Hind wing: the coalescence of MA with Rs is more obvious here than in the fore wing. The basal piece of MA (termed the r-m cross-vein by Comstock) is usually longitudinally placed (except in Berothidae), not transversely. In many species of nearly all genera of Hemerobiidae MA is not actually coalesced with Rs but is only joined to it by a cross-vein. This apparently represents a more generalized condition than the true coalescence, the latter being the result of the shortening and subsequent elimination of the cross-vein. In certain genera of Hemerobioidea the coalescence of Rs and MA exhibits unusual features. In Climacia the coalescence takes place nearly at the middle of the wing, instead of close to the base of the wing; and in Lomamyia the basal part of MA is transverse, as in the fore wing. In most of the true Hemerobiidae (apparently all except Psectra) the radial sector, shortly after its origin, is joined to R1 by a cross-vein, termed in this paper the *basal radial cross-vein*. In Hemerobius this cross-vein has nearly or entirely disappeared by shortening, so that Rs is in actual contact with R1. The position of this cross-vein varies greatly in the different genera; in Kimminsia it is proximal to the separation of MA from Rs (or of the connecting cross-vein), whereas in all other genera, so far as I am aware, it is distal to that point.

Although the families treated in this paper do not form a natural group by themselves, they do belong to one superfamily, Hemerobioidea, as defined by Tillyard (1926). Since nearly all of the Nearctic Neuroptera are referable to the Hemerobioidea, I include here a key to the families.

KEY TO THE NEARCTIC FAMILIES OF THE SUPERFAMILY HEMEROBIOIDEA

1. Fore legs raptorial .... Mantispidae
   Fore legs cursorial 2
2. Fore wings with two or more branches of Rs arising from the apparently fused stems of R1 and Rs 3
   Fore wings with all branches of Rs arising from a single Rs stem 4
3. Antennae of male pectinate; ovipositor exserted and long .... Dilaridae
   Antennae of male moniliform or filiform; ovipositor not exserted .... Hemerobiidae
4. Fore wing with recurrent humeral vein Polystoechotidae
   Fore wing without recurrent humeral vein 5
5. Cross-veins of costal area forked in fore wing Berothidae[1]
   Cross-veins of costal area not forked in fore wing 6
6. Sc and R1 free distally; gradate veins present Chrysopidae
   Sc and R1 coalesced distally; gradate veins absent .... Sisyridae

FAMILY HEMEROBIIDAE

Antennae moniliform, multisegmented, usually nearly as long as the fore wing, the first segment enlarged; ocelli absent. Prothorax much broader than long, with the lateral margins prolonged into a lobe. Legs cursorial; all coxae well developed and free, the fore coxae especially long and slender. Abdomen cylindrical or nearly so; tenth tergite of male divided into two lateral plates, the *anal plates;* tenth sternite forming an internal plate, consisting of a median *bridge*, connecting the two lateral, wing-like expansions (*wings*); the aedeagus attached to the bridge distally and supported by a median plate or two paired plates; parameres well developed, heavily sclerotized. Tenth tergite of female divided as in the male, but the plates differently shaped; eighth sternite reduced, small and heavily sclerotized.

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[1] Navas (1919) has described as a Berothid a species from Patagonia (*Naizema patagonica*) which has a recurrent humeral vein in the hind wing as well as in the fore. It is probable that further study of this species will indicate that its affinities are really with another family.

Wings subequal. Fore wing: usually having a broader costal area than the hind; Sc terminating on the costal margin, with a series of forked veinlets connecting it to the costal margin; Rs and R1 coalesced even beyond the points of origin of several of the branches of Rs, these branches arising from the common stem of R1 and Rs (R1 + Rs); Rs with from two to many branches; anterior media (MA) coalescing with stem R1 + Rs for a short distance and arising from this stem as a branch of Rs. Hind wing: with a narrow costal space, containing unbranched veinlets; Rs not coalesced with R1 beyond the origin of any branches of Rs, as in fore wing; MA coalesced with Rs for a short interval, usually only touching it; Rs, shortly after its separation from MA is connected with R1 by a cross-vein, which is sometimes so very short that Rs itself is in actual brief contact with R1.

Very few observations have been made on the life history and general biology of the Nearctic Hemerobiidae. Of the fifty Nearctic species of the family the life-history of only six is known: *Hemerobius pacificus* Banks (Moznette, 1915); *H. humulinus* Linn. (Smith, 1923; Killington, 1937); *Micromus posticus* Hagen (Smith, 1923); *M. subanticus* Walker (Smith, 1934); *Sympherobius amiculus* Fitch (Smith, 1923); *S. barberi* Banks (Smith, 1934). Fortunately, the life-history of the European species has been more thoroughly investigated, chiefly by Killington, Withycombe, and Kimmins. Of the twenty-nine species of Hemerobiidae included in Killington's monograph of the British Neuroptera, the life-history of eighteen is completely known, while that of most of the others is partially known. The following brief account of the biology of the Hemerobiidae is based mainly on the investigations of Smith in this country and those of Killington, Withycombe and a few others in Europe.

The eggs of the Hemerobiidae are elongate-oval, from .5 mm. to 1 mm. long, and usually about twice as long as wide. In most genera (e.g., Hemerobius, Kimminsia) the chorion is lightly sculptured, but in Micromus it is smooth. The incubation period lasts from five to twelve days usually, but it may extend over the winter in some species. The number of eggs deposited in nature by a single female is not certainly known. Smith has noted that in the laboratory most females lay from thirty to forty eggs, but recorded one *H. humulinus* laying 460 eggs. Normally the eggs are laid singly, on leaves, twigs, or bark.

The larvae are fusiform and look much like those of the Chrysopidae, but differ in having a smaller head, shorter body, and no pulvilli in the second and third instars. They are not trash carriers like many Chrysopids.[2] The larvae are very active in all instars, and run rapidly, jerking the head from one side to the other as they do so. The terminal segment of the abdomen is often used to aid in walking and especially in climbing. The head is very small in proportion to the rest of the larva; the eyes contain six elements and are located directly behind the antennae; both antennae and labial palpi are three-segmented; all thoracic segments are large, the larva being broadest across the metathorax and first abdominal segment; the abdomen consists of ten segments; the legs are subequal and have a single tarsal segment. As in all other Neuropterous larvae (Planipennia) the mandibles and maxillae are elongate and grooved, and are fitted together so as to form a canal leading to the pharynx. The true mouth is non-functional; in fact, immediately after the larva has hatched from the egg, the integument of the head extends over the mouth and is subsequently withdrawn into the oral cavity, which is then permanently closed by the interlocking of the roof with the floor of the cavity. Liquid food is drawn up through the mandibular canal into the pharynx by the pumping action of the pharyngeal region. There is no evidence of extra-oral digestion. The digestive tract is blind, being closed at the posterior end of the mesenteron. The minute amount of solid food taken in through the mandibular canals is not eliminated until the imaginal stage is reached, when it is ejected from the anus as a hard pellet, enclosed in a peritrophic membrane. Liquid excretion in the larva is accomplished by the Malpighian tubules (usually eight). Some of these are attached to the hind intestine near the silk reservoir, which is a thin-walled sac, opening into the rectum. The fluid secreted by the Malpighian tubules apparently diffuses through the walls into the silk reservoir and thence passes into the rectum and anus.

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[2] The statement made by Sharp (1895) that some Hemerobius larvae carry trash has been accepted by Comstock in his *Introduction to Entomology* (1935, p. 297). It is obvious from Sharp's figure of the larva, which was reproduced by Comstock, that the insect concerned was really a Chrysopid, not a Hemerobiid.

As in nearly all other Neuroptera there are three larval instars, the third being the longest. The larval period is usually very short, extending from twelve to twenty-four days; but in the late fall the third instar alone may last three weeks. The number of broods annually varies specifically, as well as geographically in one species. Killington has found that the number is from one to four in the British Hemerobiids. One European species of Hemerobius (*stigma*) has a succession of broods, without any definite break between them, the adults being found on the wing during all months of the year. In the case of the Nearctic species of which there are extensive collecting data, I have been unable to find any breaks (exclusive of the winter months) in the records of the adult captures; this is true even of the data obtained from any one state or similar area. I am inclined to believe, therefore, that there is a succession of broods in most of our species of Hemerobiids, the adults emerging continuously from the spring through the fall.

All Hemerobiid larvae are carnivorous, feeding on a variety of small, soft-bodied insects, especially plant-lice. Some larvae show a definite host preference; this is indicated by the fact that such larvae are found only (or chiefly) on certain species of plants, with which particular species of aphidids are associated. The larvae are capable of devouring a surprisingly large number of such small insects. One larva of Hemerobius reared by Withycombe (1925) consumed 79 aphidids during its development; and larvae of Kimminsia and Megalomus were found by Killington to eat from 75 to 96 of the plant-lice. The highest record of food consumed is given by Laidlow (1936), who estimates from several experiments that one larva of *Hemerobius stigma* devoured on the average three thousand eggs and nymphs of an adelgid.

At the end of the last (3rd) instar the larva seeks a sheltered place, such as a crevice in bark, and there spins a cocoon. The silk is exuded from the anus, the three terminal segments of the abdomen being greatly stretched during this process. A very loose, outer frame of the cocoon is first made, and then the inner cocoon, which is composed of an open mesh of strands. The prepupal stage begins shortly after the cocoon is completed; the head, prothorax and end of the abdomen bend downward, and the legs are drawn up. The prepupa is entirely unable to walk, or to spin another cocoon if it is removed from the first one. The prepupal stage may last from several days to several months; it is the condition in which many species hibernate. The pupal stage also may last from ten days to several months (in hibernation). Just before the adult is ready to issue, the pupa pushes its way out of one end of the cocoon and climbs to a place suitable for emergence.

The adults are usually crepuscular or even nocturnal, so that light traps provide an effective means of collecting them. They live for several months in nature, the females surviving for a longer time that the males. Both Killington and Withycombe have had representatives of several genera alive in the laboratory for two months. There are no definite records of inactive hibernation in the adult condition. The imagines are predaceous, feeding essentially on the same food as taken by the larvae; the jaws, however, are fitted for chewing, so that solid food is consumed. Three specimens of a Megalomus studied by Killington consumed an average of 315 female aphidids each during the nine weeks of their existence. The adults of *Hemerobius stigma* were found by Laidlow (1936) to devour on the average fifteen thousand eggs and nymphs of Adelges in about two months. Copulation takes place usually at night, the two insects being arranged in a linear position. Killington has described in some detail the process of mating in *Sympherobius fuscescens* (1931a): when in the presence of the female, the male runs actively about, with antennae vibrating and with the fore wings extended horizontally; on actually meeting the female, the male beats his antennae against hers for a moment, then swings about in a semi-circle and effects copulation. In this species the female regularly eats the spermatophore extracted from the male after pairing. The same behavior has been observed in other families of Neuroptera (e.g., Sisyridae) by Withycombe (1923). In most Hemerobiidae the female, after mating, usually curves the abdomen forward between the legs and brings the tip of it in contact with her mouth, suggesting the presence of a spermatophore, though none has been observed except in Sympherobius. Most of the Hemerobiidae, and perhaps all, respond to a disturbance during the day by feigning death.

Nothing is known of the parasites of the Nearctic Hemerobiidae. Killington, however, has accumulated much information about parasitism in the European species. Nearly all of the parasites are Hymenoptera, these attacking the larvae. The degree of parasitism varies considerably in the different species. Killington records that six hundred Hemerobius larvae collected in 1932 showed only .5% parasitism, whereas two hundred prepupae of Wesmaelius collected during the same year had a parasitism of 6%. The larvae are also attacked by a disease similar to flacherie (Withycombe, 1923).

The generic classification of the Hemerobiidae was originally based upon their wing venation and the genera which have been long-established show marked venational differences. It is significant also that such genera likewise exhibit striking differences in genital structure. A few neuropterists, notably Krüger (1922b), have subsequently attempted to divide these into many other genera, but in nearly all cases the peculiarities indicated are either very trivial or variable within the species concerned. Of Krüger's nine genera which include Nearctic species, the following eight are clearly not valid:

1. Schneiderobius (genotype, *Hemerobius nitidulus* Fabr., European) was established to include several Palaearctic and three Nearctic species, *moestus* Banks, *simplex* Banks, and *kokaneeanus* Currie. It is not obvious just what characteristics were supposed to be peculiar to these species;[3] but since *moestus* and *simplex* are synonyms of *stigmaterus* Fitch, which Krüger placed in Hemerobius, it is certain that these characteristics do not hold.

2. Hagenobius was based upon five Nearctic species: *Hemerobius citrinus* Hagen (genotype), *H. hyalinatus* Fitch, *H. conjunctus* Fitch, *H. dorsatus* Banks and *H. nevadensis* Banks. These species were apparently segregated because the basal piece of MA (as interpreted above) is closer to the point of separation of MA from R than it is in most other species of Hemerobius. This peculiarity exists in about 95% of the specimens of the species mentioned and it is a convenient one to use in a specific key; but it is certainly not constant enough for generic purposes. *H. nevadensis* furnishes a case in point. This species is a synonym of *H. simulans* Walker (which Krüger places in Hemerobius); the unique type of *nevadensis* has the basal piece of MA *half-way* between the basal position (as in *humulinus*) and the distal position (as in *conjunctus*).

3. Reuterobius (genotype, *Hemerobius pini* Stephens, European) included several Palaearctic and one Nearctic species, *H. cockerelli* Banks. The latter is a synonym of *conjunctus* (var. *pinidumus*) which Krüger places in Hagenobius. The genus was apparently based upon a more distal position of the basal piece of MA than was supposed to occur in Hagenobius. Such a position of this vein, however, does occur frequently in both *dorsatus* and *conjunctus*.

4. Pleomegalomus (genotype, *Megalomus pictus* Hagen, European) included one Nearctic species, *M. latus* Banks. The latter, however, is a synonym of *Megalomus moestus* Banks, which Krüger places in Megalomus. There is no mention in Krüger's paper of the reason for the new genus, but it obviously involves another variable characteristic.

5. Eurobius (genotype, *Sympherobius elegans* Stephens, European) was erected for several European and one Nearctic species, *perparvus* McLachlan. These were separated from the other Sympherobius apparently on the basis of the structure of the radial sector, which is very variable, however, in all the species of the genus.

6. Stenomicromus (genotype, *Micromus paganus* Linn., European) included, in addition to the genotype, one Nearctic species, *M. montanus* Hagen. Although it is true that *paganus* and *montanus* resemble each other more than they do other Micromus, there are no genital or other marked differences common to them.

7. Pseudomicromus was established for the single Holarctic species, *Micromus angulatus* Stephens. There are minor venational differences between this and the other Nearctic and Palaearctic species of Micromus, but they are no greater than those existing between other species of the genus. The same statement applies to the genitalia.

8. Paramicromus was erected for the Nearctic *Micromus posticus* Hagen, though Krüger took for the genotype *insipidus* Hagen, which has long been recognized as a synonym of *posticus*. There is no explanation given for this generic change,

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[3] Krüger's "monograph" of the Hemerobiidae was never completed, though the published part (Stett. Ent. Zeit., 1922, 83: 138–172) bears the subtitle, "1. Vergleichende Untersuchung des Geäders und vorläufige Übersicht und Mitteilung", and ends with the statement, "Fortsetzung im nächsten Band." Formal descriptions of his new Hemerobiid genera were not included in the published section, and it is difficult to determine from his anatomical discussion on what characteristics he intended to base his genera.

apart from the indication that the number of inner gradate veins differs by one or two from the number in other Micromus. Krüger apparently had only one specimen of *posticus,* or at most only a very small series, for the number of inner gradate veins is very unstable and far exceeds the generic limits set by him. In addition to these invalid genera Krüger also erected the genus Wesmaelius for several European species and the Nearctic *longifrons* Banks and its synonym *transversus* Banks, all of which had previously been placed in Boriomyia Banks (1905b, *nec* 1904a). As Killington points out, Wesmaelius is separated from Boriomyia not only by the wing differences mentioned by Krüger, but also by differences in the genitalia and immature stages. I have accordingly followed Killington in accepting this genus as valid.

The family Hemerobiidae has a world wide distribution. In the Nearctic region the species of the family are more numerous in the northern part and at high altitudes than in the southern part and at low altitudes. The fifty species of the family occurring in the Nearctic region are referable to nine genera, which may be distinguished by the following key:

1. Fore wing with recurrent humeral vein 2
Fore wing without recurrent humeral vein 7
2. Not more than four outer gradate veins in the fore wing ....*Sympherobius* (p. 227)
Five or more outer gradate veins in the fore wing 3
3. A conspicuous cross-vein present in the fore wing between MA and R5 (or R4 + 5) near the latter's origin ....*Wesmaelius* (p. 225)
No such cross-vein present 4
4. Rs of hind wing either in contact with R1 shortly after its separation from MA or joined to R1 by a cross-vein, which is far proximal to the origin of R5 (or R4 + 5) 5
Rs of hind wing joined to R1 by a long (usually) cross-vein, which is very close or even distal to the origin or R5 (or R4 + 5) *Megalomus* (p. 239)
5. A weak cross-vein present in fore wing between MA and MP1 + 2 shortly after the latter's origin 6
No such cross-vein present *Hemerobius* (p. 198)
6. Basal radial cross-vein in hind wing proximal to the separation of MA from Rs *Kimminsia* (p. 214)
Basal radial cross-vein in hind wing distal to the separation of MA from Rs *Boriomyia* (p. 243)
7. Fore wing with costal space abruptly narrowed at the humeral angle; three or more branches of Rs arising from stem R1 + Rs *Micromus* (p. 245)
Fore wing with costal space gradually narrowed at humeral angle; two branches of Rs arising from the stem of R1 + Rs, one proximally and one distally ....*Psectra* (p. 251)

Genus *Hemerobius* Linn.

Hemerobius Linnaeus, 1758, Syst. Nat., **1:** 549; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 29; Killington, 1937, Monogr. Brit. Neuropt., **2:** 1.
Schneiderobius Krüger, 1922, Stett. Ent. Zeit., **83:** 171.
Hagenobius Krüger, 1922, ibid., 171.
Reuterobius Krüger, 1922, ibid., 171.

Fore wing: oval or suboval, sometimes almost subtriangular; costal area usually broadened a short distance from the base; recurrent humeral vein present; costal veinlets forked; 2 or sometimes 3 branches of Rs arising from stem R1 + Rs (not including MA); basal part of MA usually near the base of wing, occasionally more distal, near the point of separation of MA from Rs; two series of gradate veins, with five or more in outer series.

Hind wing: Rs having very slight contact with MA, often connected by a cross-vein; Rs, shortly after separating from MA, diverges anteriorly and touches or very nearly touches R1; basal part of MA conspicuous, not usually sigmoidal; furcation of MP distal of the point of separation of MA from Rs; two series of gradate veins present, with five or more in outer series.

Anal plates of male well developed, each giving rise to a dorsal and ventral lobe or process; tenth sternite with the form characteristic of the family, the lateral plates well developed; parameres separate. Anal plates of female rounded; eighth sternite without the median sclerotized plate present in Kimminsia.

Genotype: *Hemerobius humulinus* Linn.[4] The strict application of the rules contained in the International Code of Zoological Nomenclature would require the recognition of *perla* as the genotype of Hemerobius, thus synonymizing the genus Chrysopa and the family Chrysopidae. The Committee on Generic Names of the Royal Entomological Society of London has proposed (Generic

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[4] The generic name Hemerobius was established by Linnaeus for a group of species now relegated to a variety of genera and families. One of the species listed by Linnaeus (*perla*) was cited by Latreille (1810, Consid. gen. Anim. Crust. Arach. Ins.: 435) as the genotype of Hemerobius. *Perla* was also designated by Leach (1815) the genotype of Chrysopa, and that usage has unfortunately been followed almost without exception until the present time.

Names of British Insects, part 4, pp. 65–80, 1937) that the International Commission of Zoological Nomenclature promulgate an Opinion suspending the rules of priority in the case of these generic names. In anticipation of that Opinion, I have used the name Hemerobius in this paper as it has been employed in the past by nearly all entomologists. *H. humulinus* was designated the genotype by Banks (1905b).

The egg is minutely sculptured. The larvae are like those of Kimminsia and Wesmaelius, having the third antennal segment much longer than the first.

The Nearctic species of the genus have been classified in the past on a variety of characteristics, such as color of the head, the place of origin of the branches of Rs, the position of the last inner gradate vein, etc. A checking of these characteristics with the genital structure in the several thousand specimens which have passed through my hands has shown that most of them vary greatly within the species, and that they are consequently of much less taxonomic value than has been supposed to be the case. The following summary indicates the taxonomic characteristics which have been used in this paper and the extent to which they may be relied upon in general.

1. Color. The color of the body as a whole is decidedly variable, especially in dried specimens. In most species the color varies from light to dark brown. Nevertheless there are extreme conditions present in certain species; thus normal specimens of *pacificus* Banks are much lighter as a whole than those of *nigrans* n. sp., in which the body is nearly black. The color of the pronotum and mesonotum is especially helpful in the ready determination of certain species; in nearly all Hemerobius these nota are traversed longitudinally by a median, yellowish stripe, bordered laterally by dark brown; but in a few species (e.g. *stigmaterus*) the median stripe is reduced to a very thin line or is completely absent. The color of the wing membrane (apart from the markings) is also very variable. In nearly all of our species of Hemerobius there is a persistent tendency for the wings to be slightly reddish; this is almost always visible in the pterostigmal region, but it often spreads over the entire wing, as in many specimens of *stigmaterus* and *bistrigatus*.[5] The wing markings, which are almost entirely confined to the fore wing, are subject to much greater variation than has been supposed. In most species the markings are of the same fundamental type, i.e., brownish maculations distributed over the entire wing; but in many species the markings are unusual because of their intensity in certain areas of the wing (e.g., *bistrigatus*).

2. Wing structure. (Figure 1.) The shape of the wing is surprisingly constant and provides the only distinction between certain species, apart from the genitalia (e.g., *pacificus* and *ovalis*, n. sp.). The shape of the costal space is very nearly the same in most members of the genus, but in a few, as *costalis* and *nigrans*, n. sp., it is sufficiently different and constant to enable easy recognition of the species. The wing venation is highly variable and many of the venational characteristics formerly regarded as specific are clearly individual, e.g., the position of the last inner gradate vein of the fore wing. There are two venational features, however, which seem to be specifically constant and which are of the greatest use in the key. One of these is the position of the basal piece of the anterior media (MA) or the

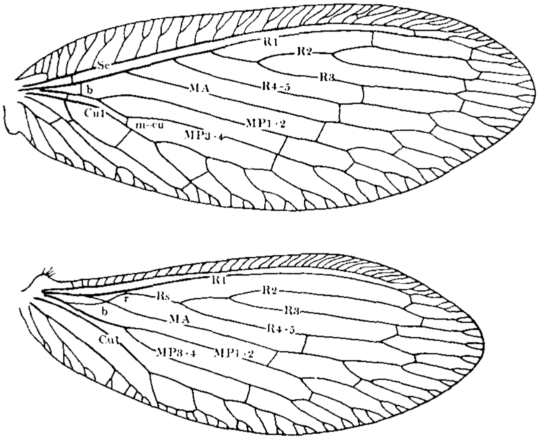

FIGURE 1. Wing venation of *Hemerobius stigmaterus* Fitch. Sc, subcosta; R1, radius; R2, R3, R4 + 5, branches of radial sector; MA, anterior media; MP, posterior media; Cu1 and Cu2, branches of cubitus; b, basal part of MA; r, basal radial cross-vein.

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[5] There seems to be no correlation between these rufous specimens and seasonal temperature or altitude, but according to Killington (1936) in the case of the European *Chrysopa carnea* Steph., which hibernates in the adult state, the imagines of the last brood change from green to reddish brown as winter approaches, the entire insect assuming a reddish hue. With the return of warm weather in spring the reddish color disappears and the insect becomes green again.

basal cross-vein of Banks' terminology. In most of the Nearctic species this vein is close to the base of the wing (e.g., *humulinus* Linn.), but in several (e.g., *conjunctus, dorsatus*) it is further distal, nearly at the point of separation of MA from R1 + Rs. The position of this vein is constant in all but two or three per cent of the specimens; in these few exceptions it is more or less intermediate in position. The other characteristic mentioned is the point of origin of the first branch of Cu1 in the fore wing. In most species this is far distal to the m-cu cross-vein, but in some (e.g., *dorsatus*) it is at or very nearly at the cross-vein. The exceptions to this do not exceed two per cent of the specimens, so that this structure, like the foregoing one, is very useful as a key characteristic, even though it is not an absolute criterion of the species concerned.

3. Genitalia. The male genitalia provide the most stable and distinctive specific characteristics. In all of the species of the genus the male genitalia are alike in fundamental structure, so that there is no difficulty in homologizing the parts. The form of the distal processes of the anal plates is helpful in a few species only, for in most the plates are similar. The parameres also are so nearly alike that I have been unable to find specific characteristics in them. The ninth sternite and the aedeagus furnish the best differences. In the figures of the genitalia I have given two views, one lateral and one dorsal, the internal structures being indicated by dotted lines within the anal plates and the ninth sternite. The terminal abdominal segments of the female are very much alike in our species and I have found them of no taxonomic value, although Killington observed a slight difference in the form of the anal plates in the British species.

Hemerobius is a widely distributed genus, occurring in Europe, Africa, most of Asia, Java, the Philippines and both North and South America. Twelve species are found within the Nearctic region, and it is probable that a few undescribed species will eventually turn up from the northwestern states. Two of the Nearctic species (*humulinus, simulans*) are Old World insects, occurring in Europe and parts of Asia; eight species (*costalis*, n. sp., *conjunctus, simulans, nigrans*, n. sp., *kokaneeanus, ovalis*, n. sp., *dorsatus, alpestris*) are restricted to the northern part of the Nearctic region or to high altitudes in the south; only two species (*humulinus, stigmaterus*) occur over all or nearly all of the region.

An unusually extensive synonymy of the Nearctic species has been created. In this revision twenty-one species have been placed in synonymy with the nine valid ones which have previously been described.[6]

The following key to the Nearctic species of Hemerobius has been based on wing and body characteristics which may be determined without dissection of the specimens. I have found it sufficient to give accurate determinations in about ninety-nine per cent of the individuals.

KEY TO THE NEARCTIC SPECIES OF HEMEROBIUS

1. Costal area of fore wing very abruptly broadened basally ....*costalis*, n. sp. (p. 213)
Costal area of fore wing not abruptly broadened basally 2
2. Cu1 in fore wing forked at or nearly at the m-cu cross-vein 3
Cu1 in fore wing not so deeply forked 4
3. Basal piece of MA in fore wing near or at the point of separation of MA from R1 + Rs; no conspicuous dark spot at m-cu cross-vein *dorsatus* Banks (p. 211)
Basal piece of MA in fore wing near the base of the wing; a conspicuous dark spot at m-cu cross-vein ....*simulans* Walker (p. 212)
4. Basal piece of MA in fore wing at or near the point of separation of MA from R1 + Rs ...5
Basal piece of MA in fore wing near the base of wing or absent 6
5. Fore wings heavily marked along Cu1 and inner gradate veins *conjunctus* var. *conjunctus* Fitch (p. 209)
Fore wings with faint markings along Cu1 or entirely without them *conjunctus* var. *pinidumus* Fitch (p. 211)
6. Fore wings with two nearly longitudinal, reddish brown streaks, one along Cu1 and the other along MA and R4 *bistrigatus* Currie (p. 208)
Fore wings with maculations or transverse bands only 7
7. Frons mottled with dark brown spots on light brown or yellow .....*alpestris* Banks (p. 207)
Frons uniformly colored or nearly so, not mottled 8
8. Costal space very narrow for its whole length, only slightly widened above separation of MA from R1 + Rs 9
Costal space at least moderately widened above separation of MA from R1 + Rs 10
9. Maculations of fore wing uniform; no pronounced markings along Cu1 and inner gradate veins; body and frons black or nearly so *nigrans*, n. sp. (p. 207)

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[6] This does not include the European synonymy of the two Holarctic species.

Maculations of fore wing along Cu1 and inner gradates; body and frons brown *kokaneeanus* Currie (p. 206)

10. Outline of distal half of fore wing not symmetrical with respect to the longitudinal axis of the wing .... *pacificus* Banks (p. 203)

Outline of distal half of fore wing symmetrical with respect to the longitudinal axis of the wing 11

11. Fore wing rather slender, apex pointed, median longitudinal stripe on pronotum very thin or absent .... *stigmaterus* Fitch (p. 202)

Fore wing broad, apex more or less rounded ..12

12. Hind margin of fore wing strongly curved *humulinus* Linn. (p. 201)

Hind margin of fore wing only moderately curved ***ovalis***, **n. sp.** (p. 205)

Hemerobius humulinus Linn.[7]

Figure 2; plate 1, figure 1

Hemerobius humulinus Linnaeus, 1758, Syst. Nat., ed. 10, **1:** 550; Killington, 1937, Monogr. Brit. Neuropt., **2:** 5 (complete European synonymy).

Hemerobius humuli Linnaeus, 1761, Fauna suecica, 383; Walker, 1853, List Spec. Neuropt. Ins. Brit. Mus., **2:** 286; McLachlan, 1868, Trans. Ent. Soc. London, **1868:** 180; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 32.

Hemerobius castaneae Fitch, 1856, 1st and 2nd Rep. Ins. N. Y.: 94.

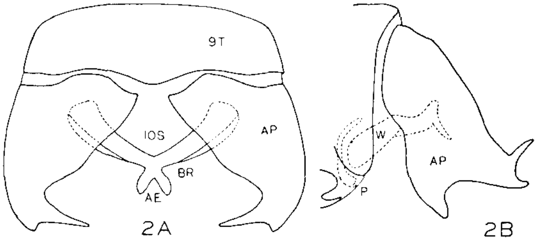
Hemerobius tutatrix Fitch, 1856, ibid.: 94.

Hemerobius gossypii Ashmead, 1895, Ins. Life, **7:** 27.

Hemerobius algonquinus Banks, 1924, Bull. Mus. Comp. Zool., **65:** 429.

Hemerobius obliteratus Walker, 1853, List Spec. Neuropt. Ins. Brit. Mus., **2:** 289.

Head from light reddish brown to yellow; cheeks below eyes dark brown; vertex the same color as frons; pronotum, mesonotum, and metanotum with a broad median yellow or very light brown stripe, widest on mesonotum, and bordered by dark brown; abdomen brown above, light brown below. Fore wing: length (average), 8 mm.; width, 3.5 mm.; broad, subtriangular, apex pointed, at least slightly so; costal space broad proximally; veins usually conspicuously spotted; membrane hyaline, with numerous light, grey-brown maculations; gradate veins at least lightly margined, usually brown and very conspicuous; only a small spot at the m-cu cross-vein, this spot being nearly always confined to the junction of the cross-vein with Cu; first fork of Cu1 not extending to m-cu; basal piece of MA near base of wing; two branches of Rs *usually* arising directly from R1 + Rs, the distal one ordinarily with only two main forks. Hind wing: hyaline, without maculations. Anal plates of male large, the upper process much larger than the lower, and possessing a prominent distal spine, which gives the appearance in lateral view that the upper process is forked distally; lower process of tenth tergite greatly reduced; tenth sternite small, only slightly broadened laterally; plates of aedeagus very small, divergent, as seen from above.



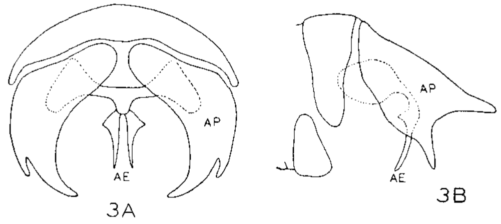


FIGURE 2. *Hemerobius humulinus* Linn. A, terminal abdominal segments of male, dorsal view; B, same, lateral view; AP, anal plate; AE, aedeagus; 9T, ninth tergite; 10S, tenth sternite; BR, bridge of tenth sternite; W, "wings" of tenth sternite; P, parameres.

FIGURE 3. *Hemerobius stigmaterus* Fitch. A, terminal abdominal segments of male (allotype), dorsal view; B, same, lateral view. Lettering as in figure 2.

Type: The type of *humulinus* is missing from the Linnean collection in London. Since the type specimen or specimens were from Europe, I have not indicated a neotype, which should also be European.

Distribution:[8] In Canada, *humulinus* is common in the eastern provinces, as Newfoundland, Nova

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[7] The name *humuli* has usually been used for this species in both American and European literature; but, as Killington has pointed out (1931b), the spelling *humulinus* was given by Linnaeus in the 10th (1758) edition of his "Systema Naturae." The form *humuli* did not appear in print until 1761, in the "Fauna suecica."

[8] In recording the geographical distribution of the species considered in this paper, I have found it impracticable and usually unnecessary to publish the

Scotia, Quebec, and even in Ontario and Manitoba (Russell, Swan River, Deepdale, Hartney, Morris, Churchill); but it is rare in Saskatchewan (Indian Head, May 5, J. de Gruyse), and British Columbia (Agassiz, March 17; Vancouver, July, March). In the United States it is common from the Atlantic as far west as about the level of central Kansas, and as far south as the level of the southern borders of Tennessee and North Carolina. I have seen only one specimen from Colorado (Golden), one from Texas (no other data), and few from North Dakota (Linton, Lake Metigashe) and South Dakota (Knox). No occurrences are known to me from any Pacific or Rocky Mountain states, except the one in Colorado, nor from the Gulf states except Florida (Fort Mead). The adults have been collected from March to October, even in the more northern parts of the range. *H. humulinus* also occurs in Europe, from Spain and Corsica in the south to the Arctic Circle in the north (Killington, 1937).

In general appearance *humulinus* resembles the western *pacificus*, and the wing markings of the two are very similar. The shape of the fore wings provides the most obvious difference for separating the two insects. The costal space of *humulinus* is broader basally than that of *pacificus;* the posterior margin of the wing is nearly smoothly curved in *humulinus,* whereas in *pacificus* the distal half of the margin is nearly straight; also the wing markings (as well as the predominating wing color) are grey in most *humulinus* but yellow-brown in *pacificus*. The anal plates of the male of *humulinus* are unique in possessing an apparently forked dorsal process.

There is no question in my mind of the synonymy of Fitch's two species, *castaneae* and *tutatrix,* with *humulinus*. The types of both of these are in the Museum of Comparative Zoology, that of the former being a female and of the latter, a male. The type of *gossypii* Ashmead is apparently lost; at any rate it is not in the National Museum collection. Ashmead identified the species with the one from Georgia which Walker recognized as *humulinus* (1853, p. 286); but since Hagen had stated (1861, p. 265) that he believed Walker's Georgia specimen to be different from the European *humulinus,* Ashmead named his species *gossypii*. There is nothing whatever in Ashmead's description which enables us to recognize any one species of Hemerobius, so that our only basis for synonymizing this with *humulinus* is Ashmead's identification of his specimen as Walker's Georgia species, and Walker's determination of the latter as *humulinus*.

Banks' *algonquinus* was based upon three faded specimens of *humulinus,* one a male; the types are in the Museum of Comparative Zoology. The identity of *obliteratus* Walker has been uncertain in the past, and Banks, in his catalogue of the Neuropteroid insects of the United States (1907), was unable to place it definitely in any genus. The type, which was from Georgia, is in the British Museum, where I have been able to examine it (1938). The species is undoubtedly *humulinus*.

Hemerobius stigmaterus Fitch

Figures 1, 3; plate 1, figure 2

Hemerobius stigmaterus Fitch, 1853, 1st & 2nd Rep. Ins. N. Y.: 93; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 30.

Hemerobius crispus Walker, in part, (nec *crispus* Stephens) 1853, List Spec. Neuropt. Ins. Brit. Mus. **2:** 288.

Hemerobius moestus Banks, 1897, Trans. Amer. Ent. Soc., **24:** 25; 1905, ibid., **32:** 31.

Hemerobius dyari Currie, 1904, Proc. Ent. Soc. Wash., **6:** 85; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 49.

Head reddish brown, frequently dark, face usually the same color as the vertex; pronotum with a very narrow median yellow stripe, or uniformly reddish brown; mesonotum and metanotum usually uniformly brown, rarely with a narrow, median yellow stripe; abdomen brown. Fore wing: length (average), 8 mm.; width, 3 mm.; narrowly oval, apex pointed; costal area narrow basally, widest above separation of MA from Rs, flattened or even slightly concave at middle of wing; membrane hyaline, but often reddish, sometimes strongly so; maculations numerous, brown or reddish brown, sometimes very diffuse; inner gradate veins usually strongly margined, outer gradates faintly so; pterostigma usually reddish, more so than in other species; only a small spot at m-cu; basal piece of MA at base of wing; first fork of Cu1 not extending to m-cu; two

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complete collecting data for all specimens. If a species has been taken at various, widely scattered localities in a state, I have merely listed that state as within the range; in such instances the insect probably occurs over all parts of that state which are ecologically satisfactory. If a species has been found at only a few localities in a state or under unusual geographical conditions, I have, of course, given complete collecting data.

branches of Rs usually arising from R1 + Rs, the outer one with two main forks. Hind wing: membrane hyaline, often reddish; pterostigma usually reddish. Anal plates of male with the dorsal process more prominent than the lower, very strongly curved inward, as seen from above; tenth sternite of moderate size, the bridge produced into a prominent, rounded papilla, to which are attached the plates of the aedeagus; the latter bear a large, ventro-lateral tooth proximally.

Types: Four females, without locality data, in the Museum of Comparative Zoology; one of these, the first in the series, I have marked as the lectotype. Fitch gives no detailed collecting data in his description of this species, but states that the insect is common in "Northern and Western States." Allotype, by present designation: Pingree Park, Colorado, August 14, 1934; R. C. Smith, collector; in the Museum of Comparative Zoology.

Distribution: This is the most widely distributed of our Hemerobius, so far as the Nearctic region is concerned. Its general range is from Labrador to British Columbia in Canada; and across the entire United States. I have seen no specimens from Montana, North Dakota, South Dakota, Kentucky, Tennessee, South Carolina, Georgia, and the Gulf states; but the lack of specimens from these states is almost certainly due only to their not having been collected, rather than to the actual absence of the species. The collecting records of *stigmaterus* indicate that the adults may be found from March to October, even in Canada. The insect apparently hibernates in the adult stage, also, for I have seen several specimens collected in snow during January in Maryland (H. S. Barber) and during December in British Columbia.

Stigmaterus is the most difficult of the Nearctic Hemerobius to identify without the use of the male genitalia. The very narrow stripe on the pronotum and the slender pointed wings are the only general characteristics which are constant enough to use in separating the insect from its close relatives. The wing markings are subject to much variation, more than in any other Nearctic species of the genus. In the majority of specimens the wing membrane is hyaline and covered with many small maculations; but such specimens grade into others in which the maculations have become so diffuse as to tint most of the membrane reddish brown. In such cases the tinting is usually most noticeable along the posterior margin of the wing from the base to the apex, extending inward to about the level of the first fork of Cu1. The color of the pterostigma of both fore and hind wings is likewise subject to much variation. In most specimens it is decidedly rufous, especially in those individuals having the diffuse wing markings; in others the pterostigma of either wing shows no trace of coloration. This characteristic, the color of the pterostigma, is therefore not a satisfactory diagnostic feature, for, as I have already mentioned, a rufous pterostigma may occur in almost any of our species of Hemerobius.

The male genitalia, on the other hand, are very distinctive. The curvature of the dorsal process of the tenth tergite can readily be seen, even without magnification; and the prominent, rounded process of the tenth sternite, at the base of the aedeagus, is a very constant and useful taxonomic structure.

The synonymy of *stigmaterus* is rather extensive, chiefly because of the variation of the wing markings. Two of the specimens (b, c, "North America") which Walker (1853) identified as the European *crispus* Stephens belong to *stigmaterus;* this has been ascertained by Kimmins' publication of a figure of the male genitalia of one of these specimens (1932, p. 87) and by my examination of the specimens themselves in the British Museum. Banks' *moestus,* which was based upon a single female now in the Museum of Comparative Zoology, is unquestionably this species. *H. dyari* Currie is likewise a synonym. This species, established for a unique female, now in the United States National Museum, was separated from *moestus* by the color of the pterostigma which, though usually reddish in *stigmaterus,* is often without color. The most obvious characteristic of *stigmaterus,* the flattened or concave costal margin, is clearly present in the type (♀) of *dyari* and is mentioned by Currie in his description. The unique type (♂) of *simplex* Banks, now in the Museum of Comparative Zoology, although slightly smaller than most specimens of *stigmaterus,* has the wing markings and genital structure typical of the latter.

Hemerobius pacificus Banks

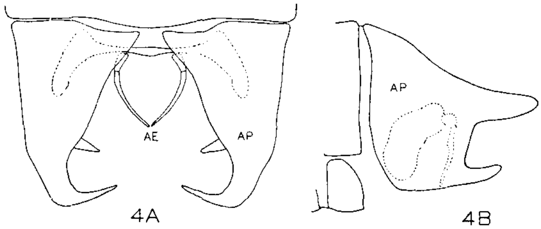
Figure 4; plate 1, figure 3

Hemerobius pacificus Banks, 1897, Trans. Amer. Ent. Soc., **24:** 24; 1905, ibid., **32:** 33.

Hemerobius pallescens Currie, 1904, Proc. Ent. Soc. Wash., **6:** 80.

Hemerobius discretus Navas, 1917, Mem. Pont. Acad. Rom., ser. 2, **3:** 5.

Head with face and vertex yellow to light brown, sometimes slightly reddish; pronotum usually with a wide median yellow stripe, rarely uniformly light brown; mesonotum mostly yellow, bordered laterally by dark brown. Fore wing: length, 9–10 mm.; width, 3.7–4 mm.; broadly triangular; posterior margin more or less straight for its distal half, not smoothly curved as in *humulinus;* costal area wide, more so basally than in *ovalis* n. sp.; membrane hyaline, maculations distinctly yellow-brown; gradate veins usually only faintly margined; spot at m-cu reduced, often absent; basal piece of MA at base of wing; first fork of Cu1 not extending to m-cu; two branches of Rs usually arising from R1 + Rs, the outer one with two main forks. Hind wing: hyaline, without maculations. Anal plates of male with the dorsal process much larger than the lower and abruptly curved inward distally; tenth sternite of normal size, the lateral extremities not greatly extended; plates of aedeagus slender, directed ventrally, not curved when seen in lateral view, but curved towards each other, their bases widely separated.



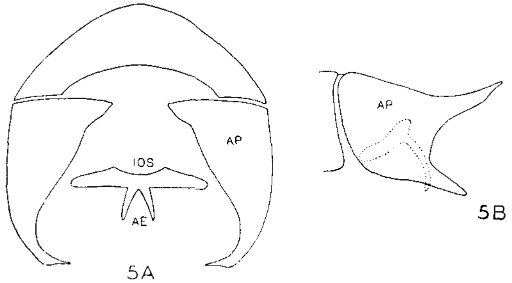


FIGURE 4. *Hemerobius pacificus* Banks. A, terminal abdominal segments of male (lectotype), dorsal view; B, same, lateral view. Lettering as in figure 2.

FIGURE 5. *Hemerobius ovalis,* n. sp. A, terminal abdominal segments of male (holotype), dorsal view; B, same, lateral view. Lettering as in figure 2.

Types: In his description of *pacificus* Banks mentioned two types, both from Olympia, Washington (T. Kincaid). Only one of these, a male, is in the Museum of Comparative Zoology; this is here designated the lectotype. I have been unable to locate the other specimen from Olympia. Allotype, by present designation: Corvallis, Oregon, December 10, 1913; in the Museum of Comparative Zoology.

Distribution: BRITISH COLUMBIA; ALASKA (Ft. Yukon, Savonoski); ALBERTA (Banff, Laggan); SASKATCHEWAN (Saskatoon); WASHINGTON; OREGON; CALIFORNIA; UTAH (Monticello, Logan, Richfield, Eureka); NEW MEXICO (Socorro Co., Sante Fe, Los Lunas); ARIZONA; COLORADO (Boulder, Ft. Collins, La Veta Pass, Colorado Springs); IDAHO (Wallace); TEXAS (Ft. Davis, Jeff Davis Co., 5000 ft., Mrs. O. C. Poling). The adults of this species have been found in most of the states and provinces from April through October; but they have also been collected in December, February and March (Oregon; British Columbia) and even January (Seattle, Washington). The general range of this insect is clearly the western part of the Nearctic region, from the Pacific to the eastern limits of the Rocky Mountains; but it is much more common in the Pacific states than further inland. I have seen one specimen of this species labelled Lincoln, Nebraska (April 10, 1908); the determination is certain because the insect is a male, but I am doubtful of the authenticity of the locality data.

In its general appearance *pacificus* resembles *humulinus* and even more closely *ovalis,* n. sp. The wings of *pacificus* are broadly triangular, as in *humulinus,* but the apical margin has a very different contour (plate 1, figs. 1, 3), the costal area is differently shaped, and the wing markings are slightly different in color. *Pacificus* can also be distinguished from *ovalis,* n. sp., by the shape of the wing, which is broadly and symmetrically rounded apically in the latter. The male genitalia are like those of *ovalis,* n. sp., in general form, but differ chiefly in the shape and position of the plates of the aedeagus.

The type (♀) of *pallescens* Currie, from Humboldt Co., California, and now in the United States National Museum, is clearly *pacificus.* Navas' *discretus,* the type of which was collected at Jemez, New Mexico, is probably *pacificus.* The type was originally in the Navas collection and its present location is unknown to me. No figure accompanies the description, and although Navas states that the insect resembles *hyalinatus* (*pinidumus*), I doubt very much that he knew the latter species. Navas describes the prothorax as having a median yellow stripe bordered by reddish brown. This almost certainly excludes *stigmaterus* as an identical species, and leaves *pacificus* as the only Hemerobius known from the southwestern states which fits Navas' description. The yellow markings on the wings of *discretus* are especially characteristic of *pacificus*. Tentatively, therefore, I have synonymized *discretus* with the latter.

Hemerobius ovalis, n. sp.

Figure 5; plate 1, figure 5

Head with face varying from yellow to brown; vertex usually yellow or light brown; pronotum with a prominent median yellow stripe, bordered by darker brown; mesonotum and abdomen mostly light brown. Fore wing: length, 8-9 mm.; width, 2.8–3 mm.; oval, with a broadly rounded apex; costal area not so broad as in *pacificus;* wing membrane hyaline, veins light brown, maculations light brown; inner and outer gradates usually distinctly margined with brown; spot of m-cu small; basal piece of MA at base of wing; first fork of Cu1 not extending to m-cu; two branches of Rs arising from R1 + Rs, the outer with two main forks. Hind wing: hyaline, without maculations. Anal plates of male with the dorsal process larger than the lower and curved inward distally; tenth sternite small, its lateral extremities not much expanded, but with a prominent dorsal, acute projection at the extremities of the bridge; plates of aedeagus prominent, curved ventrally; their bases are close together, but the plates diverge widely, though curved toward each other distally.

Holotype (♂): Claremont, California (C. F. Baker); in the Museum of Comparative Zoology. Allotype: Great Alpine Creek, Tahoe, California, July 5, 1915 (E. P. Van Duzee); in the Museum of Comparative Zoology.

Paratypes: 1 ♂, Santa Paula, California, October 11, 1917 (Woglum); 1 ♀, Gilroy, California, June (Crotch); 1 ♀, Comox, British Columbia, June 26, 1933 (J. McDunnough); 1 ♂, Nordegg, Alberta, June 12, 1921 (J. McDunnough); 1 ♀, Nordegg, June 23, 1921 (J. McDunnough); 1 ♀, Nordegg, July 29, 1921; 1 ♀, Pavilion Lake, British Columbia, June 7, 1938 (J. K. Jacob); 1 ♂, Seton Lake, Lillooet, British Columbia, May 28, 1926 (J. McDunnough); 1 ♀, Salmon Arms, British Columbia, March 2, 1925 (E. R. Buckell); 1 ♀, Nordegg, June 29, 1921 (J. McDunnough); 1 ♀, Nicolaus, California, July 27, 1935 (R. H. Beamer); all in the Museum of Comparative Zoology.—1 ♀, Nordegg, Alberta, July 21, 1921 (J. McDunnough); 2 ♀, Nordegg, July 29, 1921; 2 ♀, Nordegg, July 4, 1921; 1 ♀, Nordegg, June 22, 1921; 1 ♀, Nordegg, June 26, 1921; 1 ♀, Nordegg, June 28, 1921; 1 ♀, Nordegg, June 27, 1921; 1 ♂, Vancouver, British Columbia, August 22, 1926 (J. Stanley); 1 ♂, Vavenby, British Columbia, October, 1921 (T. A. Moillier); 1 ♂, Departure Bay, British Columbia, July 8, 1929; 1 ♀, Oliver, British Columbia, July 26, 1933 (C. B. Garrett); 1 ♀, Oliver, July 24, 1933; 1 ♀, Oliver, May 16, 1923; 1 ♀, Victoria, British Columbia, September 28, 1927 (W. Downes); 1 ♂, Oliver, August 2, 1923; 1 ♀, Oliver, June 5, 1923; all in the Canadian National Collection, Ottawa.—1 ♂, San Francisco, California, July 24, 1925 (H. H. Kiefer); 1 ♀, Paradise Valley, Mt. Ranier, Washington, July 25, 1920 (E. C. Van Dyke); 1 ♂, Nanaimo, Biol. Sta., British Columbia, June 24, 1920 (E. C. Van Dyke); 1 ♂, Clarksburg, Solano Co., California, July 24, 1931 (A. T. McClay); all in the California Academy of Sciences.—1 ♀, Los Angeles, California; 1 ♂, same June 10 (Dyar and Caudell); 1 ♀, Fks. Logan Canyon, Utah, March 12, 1934 (W. H. Thomas); 1 ♀, Sacramento, California, September, 1928 (R. A. Blanchard); all in the United States National Museum.—1 ♂, Nicolaus, California, June 27, 1935 (R. H. Beamer); 1 ♀, same, July 27, 1935; both in University of Kansas Museum.

Distribution: CALIFORNIA; BRITISH COLUMBIA; ALBERTA; ALASKA (Virgins' Bay, Tanana); WASHINGTON; WYOMING (Yellowstone National Park); OREGON (Independence); UTAH (Logan, Richfield). The adults have been collected from March to November. The species doubtless occurs also in Montana, Idaho and Nevada.

Ovalis resembles *pacificus* in general appearance and it has been nearly consistently confused with it in the past. The existence of the species did not in fact come to my attention until I had observed the striking differences in the structure of the male genitalia. The wings of *ovalis* differ from those of *pacificus* mainly in the slightly narrower costal space basally and the symmetrically rounded apex. The male genitalia show greater differences from those of *pacificus* than one would expect from the similarity of the rest of the insects. The bases of the plates of the aedeagus, which are widely separated in *pacificus,* are contiguous or nearly so in *ovalis.*

It is interesting to note that this insect has a range somewhat like that of *pacificus,* except that it is apparently absent from Arizona and New Mexico, where the latter is common.

Hemerobius kokaneeanus Currie

Figure 6

Hemerobius kokaneeanus Currie, 1904, Proc. Ent. Soc. Wash., **6:** 85; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 31.

Hemerobius hesperus Banks, 1924, Bull. Mus. Comp. Zool., **65:** 429.

Head light brown or brown, vertex lighter in color than face; pronotum with a median yellow or light brown stripe (sometimes not clearly defined), bordered by darker brown; mesonotum and metanotum mostly yellowish or light brown, often darker laterally; abdomen light to dark brown. Fore wing: length, 6-6.5 mm.; width, 6.2–6.4 mm.; slender, long, with the apex broadly rounded; costal area exceedingly narrow proximally and not much widened beyond; membrane either hyaline or distinctly brown, especially posterior half; maculations brown, usually very well developed along Cu1 and the inner gradate veins and along the longitudinal veins between the two sets of gradates; maculations at m-cu prominent; basal piece of MA at base of wing; Cu1 not forked to m-cu; two branches of Rs arising from stem R1 + Rs, the outer one with two main forks. Hind wing: membrane usually tinted with brown, frequently distinctly smoky. Anal plates of male with the upper process larger than the lower, and curved inwards, much as in *stigmaterus;* tenth sternite small, with a prominent dorsal protuberance on each "wing"; plates of aedeagus nearly straight, and with a prominent ventral tooth towards the inner side; between the plates of aedeagus there is a conspicuous sharp tooth arising from the tenth sternite.

Holotype (♀): Kokanee Mt., British Columbia, 9000 ft., August 10; in the United States National Museum. Allotype, by present designation: Thompson, Montana, August 25, 1918 (A. L. Melander); in the Museum of Comparative Zoology.

Distribution: BRITISH COLUMBIA (Hedley, August, C. B. Garrett; Kokanee Mt.; Ainsworth, April 22, 1938, G. S. Walley); WASHINGTON (Pullman); CALIFORNIA (Tahoe, July 10); MONTANA (no other data); COLORADO (Pingree Park, August, 10,000 ft., C. W. Sabrosky); QUEBEC (Cascapedia R., August 27, August 9, June 3, June 11, M. L. Prebble, W. J. Brown).

This small species may be readily recognized by the narrow costal space and the slender fore wings having rounded apices. The color markings are somewhat variable, but the well developed maculations along Cu1 and the inner gradate veins are usually present. In respect to wing markings this species resembles *conjunctus*. The male genitalia are like those of *ovalis* in general form and especially in the shape of the tenth sternite, but the latter species lacks the tooth between the plates of the aedeagus. The color of the wings is subject to extensive individual variation. The few specimens which I have seen indicate a correlation between the intensity of the brown color of the maculations and the season, specimens collected from April to June being much lighter than those collected in August. A larger series of individuals, however, might disprove this suggestion.

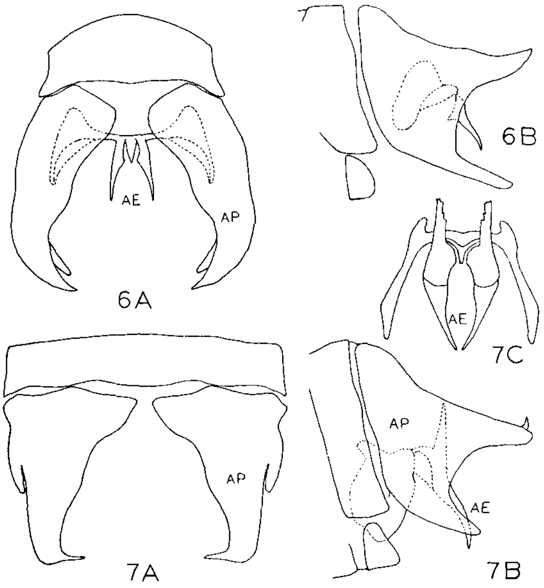


FIGURE 6. *Hemerobius kokaneeanus* Currie. A, terminal abdominal segments of male (allotype), dorsal view; B, same, lateral view. Lettering as in figure 2.

FIGURE 7. *Hemerobius nigrans,* n. sp. A, terminal abdominal segments of male (holotype), dorsal view; B, lateral view; C, dorso-posterior view of tenth sternite and aedeagus. Lettering as in figure 2.

Hesperus Banks was described from two females collected at Tahoe, California. One of these types is in the Museum of Comparative Zoology, and it is clearly *kokaneeanus*.

The occurrence of this species in Quebec is very interesting in view of the fact that all other records of the insects are western. Since several specimens of both sexes were collected in Quebec by different individuals and at different times, the locality data and the determination seem to be dependable. Apparently *kokaneeanus* is essentially a northern species which extends across Canada and enters the United States only at high altitudes.

Hemerobius nigrans, n. sp.

Figure 7

Head black, vertex nearly black, with a faint indication of some brown; antennae grey; pronotum and mesonotum uniformly black or very dark brown, sometimes a very faint indication of a thin, lighter, median streak on pronotum; abdomen dark brown. Fore wing: length, 6 mm.; width, 2 mm.; slender, oval, the apex rounded; costal area narrow, much as in *kokaneeanus;* membrane hyaline, but with many large, dark grey-brown maculations, those around the inner gradate veins usually fused to form one or two large spots, though these are no darker than the smaller maculations; spot at m-cu of the same color as other maculations; basal piece of MA at base of wing; 2 branches of Rs arising from stem R1 + Rs, the outer one with two main forks; first fork of Cu1 not extending to m-cu. Hind wing: hyaline, but with some indication of a brownish tint, occasionally smoky. Anal plates of male with the upper process larger than the lower and bearing distally a conspicuous tooth, which is directed inwards; tenth sternite and plates of aedeagus large, the former with greatly expanded extremities and a small dorsal tooth at the ends of the bridge; the plates of the aedeagus extend upwards beyond the tenth sternite, forming a pair of processes nearly as long as the rest of the plates; these upper processes have several fine teeth distally and along the inner margin; lower part of plates converging, the apices nearly touching between the plates the tenth sternite projects slightly in the form of a shallow tooth.

Holotype (♂): Mt. Lolo, Kamloops, British Columbia, June 2, 1938 (J. K. Jacob) in Canadian National Collection. Allotype: same collecting data as holotype; also in Canadian National Collection.

Paratypes: 1♂, with same collecting data as holotype; 1♀, Clinton, British Columbia, June 13, 1938 (G. S. Walley); 1♂, Great Alpine Creek, Tahoe, California, June 21, 1915 (E. P. Van Duzee); all in the Museum of Comparative Zoology.—1♀, Yellowstone Nat. Park, Wyoming, July 19, 1930 (E. C. Van Dyke); in the California Academy of Sciences.—1♀, Laramie, Wyoming, July 5, 1938; in R. C. Smith collection.

In addition to the types, I have seen five other specimens: 1♀ from Longs Peak, Colorado, 9000 ft., July 1, 1926 (E. C. Van Dyke); 1♀, Mt. Kaiser, Fresno Co., California, 10,000 ft. (E. P. Van Duzee); 1♀, La Veta Pass, Colorado, June 27; 1♀, Aspen Grove, British Columbia, May 3, 1934; 1♂, Crabtree Meadow, 10,550 ft., Tulare Co., California, July 29, 1935.

This strikingly marked species is much like *kokaneeanus* in size and shape of the wings; but it is at once distinguished by the uniformity of the maculations on the wings and the black color of the body. The male genitalia are remarkable for the dorsal extension of the plates of the aedeagus. The species will probably turn up at high altitudes throughout the western states.

Hemerobius alpestris Banks

Figure 8

Hemerobius alpestris Banks, 1908, Trans. Amer. Ent. Soc., **34:** 261.

Head brown, but with face mottled with very dark brown; one dark stripe between antennae and two thin vertical stripes on each side of the face; clypeus usually very dark brown; rest of face light brown or yellow; vertex usually median brown, with a thin stripe of dark brown bordering the antennal sockets; pronotum usually uniformly medium brown, sometimes with a faint indication of a thin, median stripe; mesonotum uniformly brown; abdomen brown. Fore wing: length, 7 mm.; 3 mm.; broadly oval; costal area very narrow, but abruptly widened above separation of MA from Rs; membrane either hyaline or somewhat smoky, especially along the posterior border; veins brown, maculations medium brown, never dark brown, and of nearly uniform intensity; spot at m-cu nearly absent; basal piece of MA at base of wing; first fork of Cu1 not reaching to m-cu; two branches of Rs arising from R1 + Rs, the outer with two main forks. Hind wing: hyaline or slightly smoky, without maculations. Anal plates of male with the dorsal process bearing a slender, distinct tooth on the inner margin near the apex; ventral process much reduced; tenth sternite of moderate size, the lateral extremities extended forwards and forming a point; plates of aedeagus straight from above and nearly straight from the side; the bridge extended in the form of a small tooth between the plates of the aedeagus.

Holotype (♂): Sugar Loaf Mt., Colorado, May 13 (S. A. Rohwer); in the Museum of Comparative Zoology. Allotype, by present designation: Pingree Park, Colorado, August 14, 1934 (R. C. Smith); in the Museum of Comparative Zoology.

Distribution: COLORADO (Longs Peak, Rocky Mt. Nat'l. Park, 9000 ft., July 12, and June 30, E. C. Van Dyke; Mt. Manitou, June 21; Pondre Canyon, August 22, 1925, R. H. Beamer, P. W. Lawson; Pingree Park, 9000 ft., August; ARIZONA (Mt. Lemon, Catalina Mts., 7000 ft., July 26; Chiricahua Mts., Cochise Co., 8–9000 ft., July 15).

This species resembles *stigmaterus* superficially, having a similarly colored thorax. It is unique among our species, however, in possessing a mottled face and the abruptly broadened costal area, which is nevertheless narrow at the base. It is evidently confined to high altitudes; none of the specimens which I have seen were collected under 8000 ft. It is probably common locally, for Dr. Smith secured nine specimens in a short time at Pingree Park in Colorado.

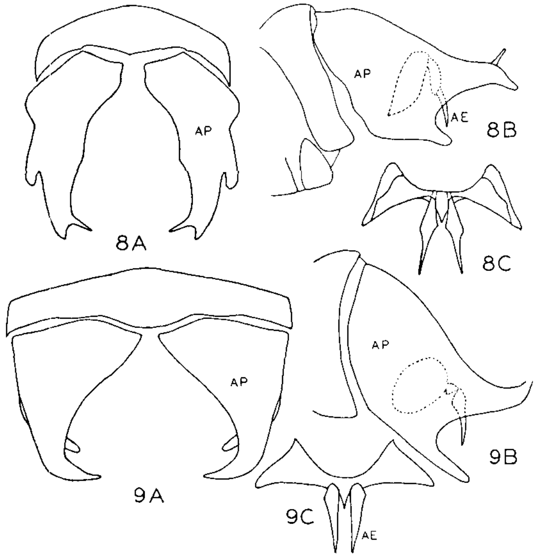


FIGURE 8. *Hemerobius alpestris* Banks. A, terminal abdominal segments of male (holotype), dorsal view; B, same, lateral view; C, dorso-posterior view of tenth sternite and aedeagus. Lettering as in figure 2.

FIGURE 9. *Hemerobius bistrigatus* Currie. A, terminal abdominal segments of male (allotype), dorsal view; B, lateral view; C, posterior view of tenth sternite and aedeagus. Lettering as in figure 2.

Hemerobius bistrigatus Currie

Figure 9; plate 1, figure 4

Hemerobius bistrigatus Currie, 1904, Proc. Ent. Soc. Wash., **6**: 79.

Face and vertex usually light brown or yellow, face sometimes darker than vertex, cheeks dark brown; pronotum with a wide median yellow stripe bordered by dark brown; mesonotum mostly light brown or yellow, bordered by darker brown; abdomen brown. Fore wing: length (average), 7 mm.; width, 3 mm.; oval, apex rounded; costal area narrow, almost as in *kokaneeanus;* wing membrane mostly tinted yellow or very light brown, except for the area between the two streaks mentioned below, which is hyaline; gradate veins not margined, and true maculations, when present, occur only along R1 + Rs; MA usually strongly margined with dark brown to the middle of wing, R4 + 5 being margined from there to apex; Cu1 and MP margined distally; two conspicuous longitudinal streaks are formed by the margination of these veins; free piece of MA present at base of wing; Cu1 not forked to m-cu; two branches of Rs arising from R1 + Rs, the outer with two main forks. Hind wing: usually hyaline, but often yellowish. Anal plates of male very much like those of *kokaneeanus,* the dorsal process of the plates being much larger than the lower and curved inward distally; lower process straight; tenth sternite with a prominent dorsal, acute projection, and with an acute tooth between the plates of the aedeagus; the latter straight and nearly parallel.

Holotype (♀): Little River, Humboldt Co., California, May 31; in the United States National Museum. Allotype, by present designation: Boyer, Oregon, August 15, 1937; in the Museum of Comparative Zoology.

Distribution: CALIFORNIA (Humboldt Co.; San Francisco, March 5, F. X. Williams; Fallen Leaf Lake, Tahoe, July 14, E. C. Van Dyke); BRITISH COLUMBIA (Vancouver, February 1 and March 8, 1931, H. B. Leech); OREGON (Boyer, May 6, July 29, August 3 and 15); IDAHO (Priest Lake, June 3, A. L. Melander).

This rare species has strikingly marked wings, which enables easy recognition of most specimens. These wing markings are very variable, however; in some specimens the margination of the veins extends to the base of MA and Cu1, whereas in others it does not extend proximally to the middle of the wing. In some specimens, also, the wing membrane is perfectly clear, while in others it is very yellow. The pterostigma is frequently reddish, which was probably responsible for Banks' synonymizing *bistrigatus* with *stigmaterus* (*moestus*). That *bistrigatus* is distinct from *stigmaterus* is proven by the difference in the male genitalia. The genital structure of *bistrigatus,* though very different from that of *stigmaterus,* is remarkably similar to that of *kokaneeanus;* the only very obvious difference is in the form of the plates of the aedeagus; in *kokaneeanus* these diverge, whereas in *bistrigatus* they are parallel. This is a surprisingly trivial difference in view of the great discrepancy in wing markings.

Hemerobius conjunctus var. *conjunctus* Fitch

Figure 10

Hemerobius conjunctus Fitch, 1856, 1st and 2nd Rept. Ins. N. Y.: 94; Hagen, 1861, Synop. Neuropt. N. A.: 203: Banks, 1905, Trans. Amer. Ent. Soc., **32:** 35.

Hemerobius venustus Banks, 1897, Trans. Amer. Ent. Soc., **24:** 25; Banks, ibid., **32:** 49.

Hemerobius citrinus Hagen, 1861, Synop. Neuropt. N. A.: 204; Krüger, 1922, Stett. Ent. Zeit., **83:** 153.

Hemerobius glacialis Currie, 1904, Proc. Ent. Soc. Wash., **6:** 88.

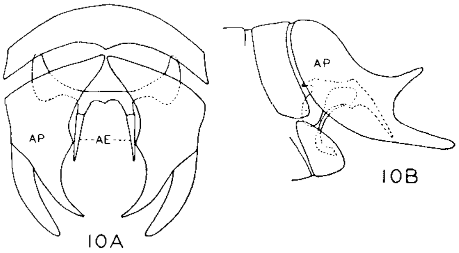
Hemerobius caudelli Currie, 1904, ibid., p. 87.

Hemerobius kootenayensis Currie, 1904, ibid., p. 88.

Hemerobius cockerelli Banks, 1901, Psyche, **9:** 286.

Head with face and cheeks dark reddish brown, frequently almost black; vertex yellow or light brown, often slightly reddish, but always lighter than most of face; antennae yellow; pronotum, mesonotum and metanotum with a wide median yellow stripe, bordered laterally by dark brown, which is usually darker on the pronotum than on the following segments; abdomen light to dark brown. Fore wing: length, 5.3 to 8 mm.; width, 3 to 3.5 mm.; oval, slightly pointed; costal area of moderate width, about as in *dorsatus;* membrane hyaline, maculations grey-brown; most of the maculations are faint, but a larger and darker spot is present in the region of the fork of MP and the first fork of Cu1, the latter one being much longer than that of *simulans;* smaller dark spots are also present on Cu1 distally and along the inner and outer gradate veins, the latter therefore being heavily and broadly margined; basal piece of MA usually at or near the point of separation of MA from Rs; first fork of Cu1 not extending to m-cu cross-vein; two branches of Rs arising directly from R1 + Rs, the outer with two main forks. Hind wing: hyaline, without maculations. Anal plates of male with the lower process slender and longer than the dorsal one, which is curved inwards; tenth sternite rather small, the lateral plates not greatly extended; plates of aedeagus widely separated, with a shallow tooth between them, and each plate with a prominent ventral tooth proximally, readily visible in lateral view.

Holotype (♂): (no locality data) in the Museum of Comparative Zoology; the specimen was probably collected in New York, for Fitch, in his report on the New York insects, usually mentioned the state in which his specimens were collected if they were not secured in New York. Allotype, by present designation: Baddeck, Cape Breton, Nova Scotia, September 14, 1931 (A. G. B. Fairchild).



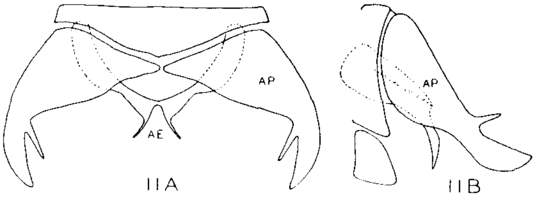


FIGURE 10. *Hemerobius conjunctus* var. *conjunctus* Fitch. A, terminal abdominal segments of male (holotype), dorsal view; B, same, lateral view. Lettering as in figure 2.

FIGURE 11. *Hemerobius dorsatus* Banks. A, terminal abdominal segments of male (lectotype), dorsal view; B, same, lateral view. Lettering as in figure 2.

Distribution: LABRADOR (Hopedale, July, W. W. Perrett); NEWFOUNDLAND (St. Johns, June); QUEBEC (Cascapedia; Seven Isles, July 28; Knowlton, August; Kazubazun, June; Bradore Bay, July); NOVA SCOTIA (Kentville, June, July; S. Milford, June); PRINCE EDWARD ISLAND (Hampton, August); MAINE (Mt. Katahdin); VERMONT (White Horse, July 3, H. G. Dyar); NEW HAMPSHIRE (Mt. Washington; Ossipee Mt., August); NORTH CAROLINA (Black Mts., June); TENNESSEE (Newfound Gap, Smoky Mts., September); ON-

TARIO (Biscotasing, June–September; Ottawa, April); SASKATCHEWAN (Indian Head, June, August, J. de Gryse); ALBERTA (Lake Louise, August 16, 5600 ft., G. S. Walley; Moraine Lake, August 1, J. McDunnough); BRITISH COLUMBIA (Clinton, June 19, 1938, J. K. Jacob; Nelson, June 1, A. A. Dennys; Kootenay District, July); ALASKA (Healy, June 24, J. M. Aldrich; Savoniski, Naknek Lake, July, A. J. Basinger); MONTANA (No other data); WYOMING (West Yellowstone, July 16, E. C. Van Dyke); COLORADO (Pingree Park, August 14, R. C. Smith; Sherbon, Eagle Co., 7900 ft., August 11, C. Clagg; Gothic, 9500 ft., July 16, C. P. Alexander; Rocky Mt. National Park, July 25, H. H. Ross; Berthoud Pass, 10,000 ft., July 24, H. H. Ross); NEW MEXICO (Las Vegas, August, H. S. Barber; Las Vegas Mts., T. D. A. Cockerell; Taos, August 20, 1923, R. H. Beamer).

This is a northern insect; it is mainly Canadian, extending into the United States only along the Rocky and Appalachian Mountain ranges. Although I have seen a great many specimens of *conjunctus,* they have been collected at widely scattered localities, which have consequently been recorded above.

This species apparently exists in two forms. The typical one (var. *conjunctus*) is heavily marked and easily recognized; the other form (var. *pinidumus* Fitch), which is redescribed below, differs in having almost no wing markings whatever, in addition to being much smaller. Most of the specimens which I have seen of these forms are strikingly different, but I have been led to regard them only as forms of one species for two reasons. In the first place, some of the smaller specimens possess definite markings and more or less grade into the typical *conjunctus;* and secondly, the male genital structure of the two is absolutely identical, even in the complicated details. The typical *conjunctus* is much more common than the smaller and paler form. Many entomologists would doubtless question the status of *pinidumus* as a variety or form of any sort, since its geographical range is within that of the typical *conjunctus.* However, inasmuch as the pale form has been described as a separate species, I have considered it advisable to retain a varietal name for such individuals.

The genital structure of the males of *conjunctus* resembles superficially that of *stigmaterus,* at least when viewed from above; but the aedeagus and tenth sternite are very different. The plates of the aedeagus are unlike those of most of our Hemerobius in that they are widely separated proximally. The wing markings of var. *conjunctus* are very distinctive. The long, dark brown maculation on the fore wing, extending from the fork of MP to the first fork of Cu1, and the heavy spots along Cu1 and the inner gradates are a combination not found in other species. The position of the free part of MA in the fore wing adds to the obvious features of this insect, although that condition also occurs in var. *pinidumus.* In spite of the fact that the position of the free part of MA is subject to some individual variation, in fully 90% of the specimens of *conjunctus* which I have seen this part of the vein is close to its separation from Rs.

An extensive synonymy of var. *conjunctus* has been established. The type of *cockerelli* Banks (in the Museum of Comparative Zoology) is a male and an examination of its genital structure shows it to be *conjunctus.* The other species which have been placed above as synonyms of *conjunctus* are based upon females, with the possible exception of *citrinus;* but their wing structure and markings clearly indicate their specific identity. *Venustus* Banks (type in the Museum of Comparative Zoology) was founded on a heavily marked specimen of *conjunctus* and has already been placed in synonymy of the latter by its author (Banks, 1905b, p. 49). Currie's three species (*glacialis, caudelli, kootenayensis*), the types of which are in the United States National Museum, were based upon unique females collected in the Kootenay District of British Columbia, and were separated from previously described species on the size (alar expanse greater or less than 12 mm.), or on the position of one of the gradate veins, or on the position of the point of forking of the "third radial sector." These venational details are of course subject to great individual variation, as I have pointed out above, and have no specific value. In all respects the types, which I have been able to examine, are typical *conjunctus. Citrinus* was described very briefly by Hagen (1861) and no collecting data were given except "North America." Hagen did mention that the wings were yellow; and Krüger (1922b), who has examined the type in the Berlin Museum, states that the free basal piece of MA (in the terminology of the present paper) is close to the separation of MA from Rs. *Conjunctus* is the only Nearctic species to which these two characteristics would apply.

Hemerobius conjunctus var. *pinidumus* Fitch

Hemerobius pinidumus Fitch, 1856, 1st and 2nd Rep. Ins. N. Y.: 95.
Hemerobius hyalinatus Fitch, 1856, ibid., 95.
Hemerobius canadensis Banks, 1897, Trans. Amer. Ent. Soc., **24:** 26.

Head varying from yellow to light brown, the face usually darker than the rest, as in var. *conjunctus;* pronotum with a median yellow stripe, bordered by dark brown; mesonotum and metanotum light brown, almost uniformly colored, the lateral margins only slightly darker than the median area; abdomen brown. Fore wing; length, 5–6 mm.; width, 2.5–3 mm.; membrane hyaline, often lightly tinted with yellow-brown; costal area as in var. *conjunctus;* wing markings usually absent, but occasionally a faint indication of them is present; MA as in var. *conjunctus;* first fork of Cu1 not extending to m-cu; Rs as in var. *conjunctus*. Hind wing: hyaline, sometimes faintly yellow, without maculations. Male genitalia as in var. *conjunctus*.

Holotype (♂): (no locality data) in the Museum of Comparative Zoology; the specimen was probably collected in New York State, as in the case of the type of var. *conjunctus*. Allotype, by present designation: Aylmer, Quebec, July 29, 1927 (G. S. Walley); in the Museum of Comparative Zoology.

Distribution: QUEBEC (Kazubazun, August 16, G. S. Walley; Fairly Lake, May, June, R. Ozburn; Aylmer, July 29, August 3, G. S. Walley; Covey Hill, July 2; Sherbrooke, May 10); MAINE (N. E. Bay); NEW HAMPSHIRE (Hampton, May 10, S. A. Shaw); MASSACHUSETTS (Cambridge); NEW YORK (Ithaca, May 17); WISCONSIN (Brule, August 16); MINNESOTA (Cass Lake, August 1, R. H. Daggy); COLORADO (Longs Peak, 9000 ft., July 12, E. C. Van Dyke); BRITISH COLUMBIA (Kamloops, August 1, G. J. Spencer).

This form differs from the typical one by its smaller size and the absence of wing markings, although in some specimens there is an indication of the markings as present in the latter. *Hyalinatus* Fitch, the type (♂) of which is in the Museum of Comparative Zoology, is a synonym of this form. *Canadensis* Banks, the type (♀) of which is in the same Museum, is also a synonym and since 1907 has been so regarded by Banks.

Hemerobius dorsatus Banks

Figure 11; plate 1, figure 7

Hemerobius dorsatus Banks, 1904, Can. Ent., **36:** 61; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 34.

Head and face yellow or light brown, usually with a narrow, median dark brown stripe leading up from the clypeus; antennal sockets margined with dark brown; pronotum, mesonotum and metanotum with a continuous light brown or yellow median stripe, bordered by dark brown; abdomen dark brown. Fore wing: length (average) 9 mm.; width, 3.7 mm.; broadly oval; apex rounded; costal area much broader basally than in *simulans;* membrane hyaline with many brown maculations; veins brown, usually light; gradate veins margined lightly with brown; only a small brown spot at the first fork of Cu1 and usually two similar spots more distally on Cu1; basal part of MA at or very near the separation of MA from Rs; Cu1 forked to or very nearly to the m-cu cross-vein; two or three branches of Rs arising directly from R1 + Rs, but when there are only two such branches the outer one has three main forks. Hind wing: hyaline, but with Cu1 margined with brown, especially distad of the first fork. Anal plates of male with the lower process broad, the dorsal process very small, in the form of a slender tooth; tenth sternite well developed and curved slightly, the plates of the aedeagus divergent.

Types: The three cotypes of this species are in the Museum of Comparative Zoology: 2 ♀, Ft. Collins, Colorado, August; and 1 ♂, Veta Pass, Colorado, July 1. The latter specimen is here designated the lectotype.

Distribution: COLORADO (Sheephorn Eagle Co., August 1, 7900 ft., C. Clagg; Williams Fork, Grand Co., July, 8300 ft.; Summit, August, 8211 ft.; Rocky Mt. Nat'l. Park; Platte Canyon; Veta Pass; Vega Pass; Ft. Collins, August); UTAH (St. George, July 21, E. W. Davis; Provo, July 12); BRITISH COLUMBIA (Chilcotin, August 10, G. J. Spencer; Clinton, June, J. K. Jacob; Jesmond, July; Rolla, July, P. N. Vroom); ALBERTA (Nordegg, July 3–August 8, J. McDunnough; Lethbridge, July 28, E. H. Strickland, and September, H. L. S. Seams; Banff, August; Peace River District, July 19, L. S. Russell; Waterton Lakes, June 24, J. McDunnough; Banff, July, August); SASKATCHEWAN (Saskatoon, August 19, K. M. King); MACKENZIE DISTRICT (N. W. T.) (Cameroon Bay, Great Bear Lake, July 16, T. N. Freeman); ALASKA (Savonoski, Naknek Lake, July, J. S. Hine). This is another northern Hemerobius, so far recorded only from western Canada, Alaska, and high altitudes in Colorado and Utah. The adults have been collected from late June through August.

This species resembles *simulans* in habitus but can readily be distinguished from it by the presence of the extra branch of Rs in the fore wing, as well as by the distal position of the basal part of MA, though the latter does not always hold. The anal plates of the male are very distinctive in possessing the tooth-like dorsal process.

Hemerobius simulans Walker

Figure 12, plate 1, figure 6

Hemerobius simulans Walker, 1853, List. Spec. Neuropt. Ins. Brit. Mus., **2:** 285; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 33; Kimmins, 1932, Ent., **65:** 87; Killington, 1937, Monogr. Brit. Neuropt., **2:** 18.

Hemerobius crispus Walker (in part, d, e) *nec* Stephens, 1853, ibid.: 288; Kimmins, 1932, Ent., **65:** 88.

Hemerobius orotypus Wallengren, 1870, Ofv. K. Vet.-Akad. Förhandl., **27:** 155; McLachlan, 1899, Ent. Mo. Mag., **35:** 131; Killington, 1929, Trans. Ent. Soc. Hamps. S. Eng., **1929:** 19.

Hemerobius placidus Banks, 1908, Trans. Amer. Ent. Soc., **34:** 260; Kimmins, 1932, Ent., **65:** 87, fig. 1B.

Hemerobius nevadensis Banks, 1904, Can. Ent., **36:** 61; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 35.

Head varying from light reddish brown to brown; antennae usually greyish yellow; pronotum with a median yellow or yellow-brown stripe, not so broad as in *humulinus;* mesonotum and metanotum yellow or light brown above, darker brown laterally; abdomen usually dark brown or even black. Fore wing: length (average) 8 mm.; width, 2 mm.; slender, pointed; costal area unusually narrow at the very base; widest above separation of MA from Rs; first fork of Cu1 at or very nearly at the m-cu cross-vein; wing membrane hyaline, often slightly brownish, with faint brown maculations; inner and outer gradate veins faintly margined; a very prominent dark brown spot around m-cu and the first fork of Cu1; sometimes a few other spots occur on the more distal part of Cu1; two branches of Rs arising directly from R1 + Rs, the outer with two main forks. Hind wing: hyaline, faintly brown, without maculations. Anal plates of male with a well developed dorsal process and a more slender ventral one; the dorsal process curved inward slightly at its tip; tenth sternite small; aedeagus directed ventrally at its origin, but curved sharply upwards distally, in side view appearing almost semi-circular; bridge of tenth sternite projecting posteriorly over the proximal portion of the aedeagus; lateral extremities of tenth sternite broadened and flattened.

Holotype (♂): St. Martin's Falls, Albany River, Hudson's Bay; in the British Museum of Natural History. Allotype, by present designation: Holliston, Massachusetts, September 8 (N. Banks); in the Museum of Comparative Zoology.

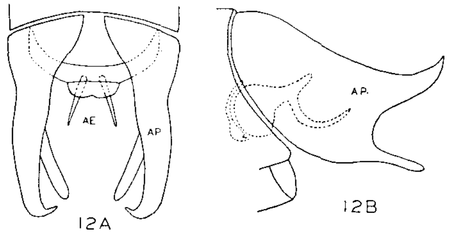


FIGURE 12. *Hemerobius simulans* Walker. A, terminal abdominal segments of male, dorsal view; B, same, lateral view. Lettering as in figure 2.

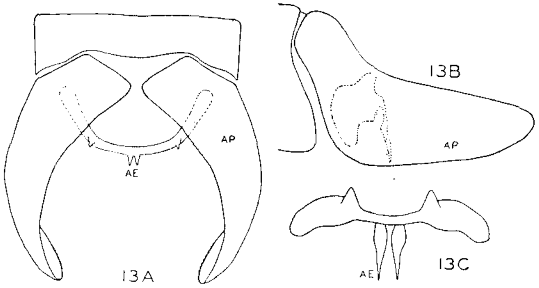


FIGURE 13. *Hemerobius costalis,* n. sp. A, terminal abdominal segments of male (holotype), dorsal view; B, same, lateral view; C, posterior view of tenth sternite and aedeagus. Lettering as in figure 2.

Distribution: QUEBEC (Wright, May 19; Thunder River, August; Wakefield, July 14; Queen's Park, July 30; Laniel, July); ONTARIO (Ottawa, May 20, August; Niagara Glen, June 1; Biscotasing, July 15; Tinagami, September 10; Asperitos Isl., Georgian Bay); NEWFOUNDLAND (St. Johns, July 21); NEW BRUNSWICK (Fredericton, May); ALBERTA (Nordegg, June 17, July 22, J. McDunnough; Laggan, July 10; Edmonton, April 28); ALASKA (Tanana, June 24); BRITISH COLUMBIA (Salmon Arm, April, November, A. A. Dennys); MAINE (Mt. Katahdin); MASSACHUSETTS (Peru, August 26; Amherst, April 29); NEW HAMPSHIRE (White Mts., August 25, C. P. Alexander); NEW YORK (Lake Placid, August 12; Fulton Co., Sep-

tember); MICHIGAN (Whitefish Point; Isle Royale, August, C. Sabrosky). This is one of our two Holarctic species of Hemerobius; in Europe, according to Killington, *simulans* ranges from the Pyrenees and Carpathians to northern Scandinavia. It has also been recorded in Greenland and eastern Siberia. In the Nearctic region it has been taken in the adult stage from April to the middle of September.

Simulans resembles *humulinus* in general appearance, but has more slender wings, a heavier spot at m-cu in the fore wing, and the deeper first fork of Cu1. The male genitalia are unique among our species of the genus in having a dorsally curved aedeagus.

The synonymy of *orotypus* Wallengren has been demonstrated by Kimmins (1932), who has published a figure of the male genitalia of *simulans*. The two specimens (d, e) from Nova Scotia determined by Walker (1853, p. 288) as *crispus* Stephens are also *simulans*, as already stated by Kimmins (1932). Banks' *placidus*, the types of which are in the Museum of Comparative Zoology, is likewise this species; two of the types are males and their genital structure is identical with that of the type of *simulans*, which I have been able to examine in the British Museum. It is my conviction that *nevadensis* Banks is also this insect. The type of *nevadensis* is a female, with faded wings; Cu1 is deeply forked, as in *simulans*, and there is a large, though faint, spot around m-cu. The basal part of MA in the fore wing is not at the very base of the wing, as is usual in *simulans*, but is half way from the basal position to the separation of MA from Rs.[9] As I have already mentioned, however, the position of this vein does not hold constant in *all* specimens of this species or of any other Hemerobius, and I regard the type of *nevadensis* as an example of this abnormal condition. So far as our present records are concerned, the type locality of *nevadensis* (Ormsby Co., Nevada) is far removed from any other locality at which specimens of *simulans* have been taken, the nearest being British Columbia and Alberta; but I suspect that further collecting will reveal the presence of *simulans* in several of the Rocky Mountain states.

Hemerobius costalis, n. sp.

Figure 13

Head varying from yellow to brown; antennae yellow; pronotum with a median yellow or light brown stripe, bordered laterally with dark brown, much as in *humulinus;* mesonotum and metanotum yellow or light brown above, somewhat darker laterally. Fore wing: length (average): 8 mm.; width, 3 mm.; subtriangular; costal margin strongly convex basally, the costal area very wide; apex pointed; first fork of Cu1 extending to about the level of m-cu; basal part of MA at the base of the wing; two branches of Rs arising directly from R1 + Rs, the outer with either two or three main forks; wing membrane hyaline, sometimes faintly yellowish, with light greyish brown maculations; inner and outer gradates faintly margined with grey-brown. Hind wing: hyaline, without maculations. Anal plates of male with a stout ventral lobe, but no dorsal process; the lower edge of the anal plates turned upwards and bearing numerous denticulate tubercles along the distal part of the turned edge; tenth sternite prominent, with a large pointed lobe at the ends of the bridge; viewed from above, the extremities of the sternite curve slightly ventrally; aedeagus of moderate size, its plates slender as viewed from the side, and possessing only a small anterior projection.

Holotype (♂): Eastport, Maine, July 14, 1909 (C. W. Johnson); in the Museum of Comparative Zoology. Allotype: Mt. Greylock, Massachusetts, August 5 (C. W. Johnson); in the Museum of Comparative Zoology.

Paratypes: 2♂ Cameron Bay, Great Bear Lake, Mackenzie, August 1, 1937 (T. N. Freeman); 1♀, 1♂ same, August 6; 1♂, same, August 18; 1♀ same, August 2; 1♂, Katmai, Alaska, August (J. S. Hine); 1♀, 1♂, Savonoski, Naknek Lake, Alaska, July (J. S. Hine); all in the Museum of Comparative Zoology.—1♂, Banff, Alberta, July 30, 1932 (C. B. Garrett); 3♂, Cameron Bay, Great Bear Lake, Mackenzie, August 1, 1937 (T. N. Freeman); 1♂, same, August 2; 2♂, same, July 27; 2♂, same, August 20; 1♂, 1♀, same, August 18; 1♀, Fort Wrigley, Mackenzie R., July 27 (C. H. Crickmay); 1♀, Keremeos, British Columbia, August 3 (C. B. Garrett); 1♀ Sioux Lookout, Ontario, June 19, 1919 (J. Russell); all in the Canadian National Collection, Ottawa.—2♀, 2♂ Savonoski, Naknek Lake, Alaska, July 25, 1919 (J. S. Hine); 1♀, same, August 1, 1919; all in the Ohio State University Museum.

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[9] Banks has stated (1905b, p. 35) that the "basal cross vein connecting media to radius ends near origin of first radial sector," but this is hardly the case. The basal piece of MA (basal cross-vein) is only about half-way out to the point of separation of MA from Rs.

In addition to the types, I have also seen specimens of this species from the following localities: Knowlton, Quebec; White Mts., New Hampshire; Grand Isle, Vermont; Newton, Massachusetts; Digby, Nova Scotia; Waubamic, Ontario; Cascade Lodge, Rocky Mt. Nat'l. Park, Colorado; Great Slave Lake, Mackenzie; and Anclosage, Alaska. The adults have been collected from June through August.

This species has been identified in the past as the European *H. marginatus* Stephens. Walker (1853, p. 286) determined a specimen of Hemerobius from Nova Scotia as *marginatus,* and although Hagen (1861) was of the opinion that Walker's specimen was different from *marginatus,* he did not propose a new name for the species. McLachlan subsequently (1899) identified a female from New Hampshire as *marginatus,* and Banks (1905b), who at that time had no European specimens available for comparison, accepted the determination as probably correct. Killington (1937, p. 65) figures a lateral view of the apex of the male abdomen of *marginatus,* but does not describe or figure the tenth sternite. I therefore dissected the genitalia of several European males of *marginatus* contained in the Museum of Comparative Zoology. These dissections revealed a structure very different from that of our Nearctic specimens. In a posterior view of the sternite of the European specimens the lateral extremities of the sternite are seen to be directed dorsally, not ventrally, as in our insects, and in a lateral view the prominent, pointed dorsal lobes of our specimens are lacking in the European ones. The anal plates, although having the same general form in both species, are longer and more slender in the Old World specimens. The wings also show some differences, those of the latter being relatively shorter and broader and having a wider costal area. It seems clear, therefore, that there are really two species concerned, the Nearctic one being named here *costalis.* The close relationship between the two is emphasized by the similarity of the anal plates, which are very different from those of all other Nearctic and Palaearctic species. It is very probably either that one of these species has been derived directly from the other, or that both have been derived from an immediate, common ancestor. In this connection it is interesting to note that both are restricted to northern parts of their respective regions. According to Killington, *marginatus* occurs in northeastern Europe from Finland and Scandinavia and the British Isles to southern France. *Costalis* apparently extends across Canada from Nova Scotia to British Columbia, Yukon, Mackenzie and Alaska; it enters only into northern New England and the northern part of the Rocky Mountain region.

Costalis is readily distinguished from the other Nearctic species of Hemerobius by the very broad costal area. So far as its wing venation is concerned, it is closest to *simulans* and *dorsatus,* both of which have the first fork of Cu1 extending to the m-cu cross-vein.

Genus *Kimminsia* Killington

Kimminsia Killington, 1937, Monogr. Brit. Neuropt., **2:** 254.

Boriomyia Banks, 1905 (*nec* 1904), Trans. Amer. Ent. Soc., **32:** 36.

Fore wing: oval; costal area broadened basally; recurrent humeral vein present; costal veinlets forked; two or sometimes three branches of Rs arising from stem R1 + Rs (not including MA); basal piece of MA either absent (usually) or present at base of wing; MA connected to MP 1 + 2 by a strong cross-vein just beyond the origin of the latter; two series of gradate veins, more than five veins present in the outer series. Hind wing: Rs coalesced with MA for a considerable distance and joined to R1 by a cross-vein before the separation of MA from Rs; basal piece of MA conspicuous, not usually sigmoidal; furcation of MP at about the same level as (or even proximal to) the separation of MA from Rs; two series of gradate veins, more than five in the outer series.

Anal plates of male well developed, with a distal process or with rows of teeth ventrally; tenth sternite with broad "wings," each bearing a distal process ventrally; a single median plate of the aedeagus; parameres fused anteriorly. Anal plates of female broad; eighth sternite with a median sclerotized plate.

Genotype: *Hemerobius betulinus* Strøm.

The immature stages of all the Nearctic Kimminsia are entirely unknown. According to Killington the egg and larva of the European species are similar to those of Hemerobius.

Most of the Nearctic Hemerobiids previously placed in Boriomyia must now be referred to Kimminsia. Banks' description of Boriomyia and his designation of the genotype (*Hemerobius disjunctus* Banks) were contained in his revision of the Nearctic Hemerobiidae (1905b); but the generic name was used by him the preceding year in a local (Washington, D. C.) list of Neuroptera for *H. fidelis* Banks and *H. speciosus* Banks, without description or genotype designation.[10] In 1930 Banks established the subgenus Allotomyia for *fidelis* and *speciosus* and subsequently raised that to a genus (1935). Killington has correctly pointed out that since Boriomyia was used for *fidelis* and *speciosus* in 1904, even without type citation, it must be used for those species, Allotomyia being a synonym. He accordingly established the genus Kimminsia for the other species (*disjuncta,* etc.) formerly included in Boriomyia also.

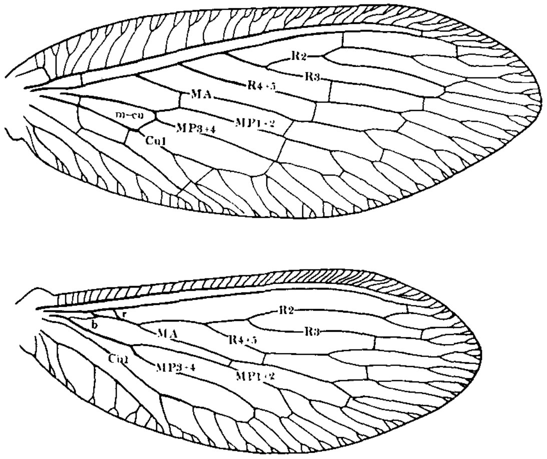

FIGURE 14. Wing venation of *Kimminsia disjuncta* (Banks). Lettering as in figure 1.

The species now referred to Kimminsia have been classified in the past on essentially the same characteristics used in Hemerobius. The foregoing remarks regarding the taxonomy of Hemerobius likewise apply here; but the color of the head and thorax is specifically more constant in Kimminsia than in Hemerobius and hence can be used for determination with greater accuracy. Also the ninth sternite of the female provides very good taxonomic characteristics in the form of the ventral sclerotized plate.

Kimminsia, like Hemerobius, has a wide distribution, having been recorded from Europe, Africa, New Zealand, and North and South America. Ten species have been found in the Nearctic region; most of these are restricted to the northern part or to high mountains further south.

KEY TO THE NEARCTIC SPECIES OF KIMMINSIA

1. Pronotum with a conspicuous longitudinal yellowish stripe, bordered laterally with dark brown 2
   Pronotum without such a median stripe 6
2. Mesonotum with a median yellow stripe, extending the length of the segment 3
   Mesonotum with the anterior part of the median yellow stripe marked with a dark brown transverse band or two brown spots 4
3. Face with the upper part very dark brown, the lower part light brown and the transition very abrupt ....*coloradensis* Banks (p. 217)
   Face uniformly dark brown or if the upper part is darker than the lower, the transition is very gradual ....*disjuncta* Banks (p. 215)
4. Fore wings with heavy maculations between Cu1 and the posterior border; almost no maculations elsewhere ....*posticata* Banks (p. 218)
   Fore wings with the maculations more nearly uniformly distributed over the entire wing ...5
5. Anal plates of male with a very long ventral process, inwardly curved; eighth abdominal sternite of female consisting of a small median plate without gonapophyses; maculations of fore wing at the gradate cross-vein between MP3 + 4 and Cu1 strongly developed *furcata* Banks (p. 219)
   Anal plates of male without such a curved ventral process; eighth abdominal sternite of female with a pair of tapering, posterior gonapophyses; maculations of fore wing at the gradate cross-vein between MP3 + 4 and Cu1 weakly developed ....*involuta,* n. sp. (p. 219)
6. Face, vertex and pronotum light yellowish brown, with scattered red specks *longipennis* Banks (p. 221)
   Face, vertex and pronotum not so marked 7
7. Fore wing without maculations (except a faint darkening near end of Cu1); veins not spotted *brunnea* Banks (p. 221)
   Fore wing with conspicuous maculations; veins spotted 8
8. Fore wing without distinct transverse bands *pretiosa* Banks (p. 223)
   Fore wing with distinct transverse bands 9
9. Mesonotum with dark brown along anterior border, and light brown behind; wing membrane hyaline or nearly so ...*schwarzi* Banks (p. 223)
   Mesonotum uniformly light brown; membrane somewhat smoky ....*fumata,* n. sp. (p. 225)

Kimminsia disjuncta (Banks)

Figures 14, 15

Hemerobius disjuncta Banks, 1897, Trans. Amer. Ent. Soc., **24:** 25.

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[10] Mr. Banks has explained to me that although his revision was published after the Washington list, it was sent off for publication before the latter, which did not therefore include genotype designation.

Boriomyia disjuncta Banks, 1905, Trans. Amer. Ent. Soc., **32:** 39.

Hemerobius frostinus Navas, 1933, Boll. Soc. Ent. Ital., **65:** 109, fig. 5.

Face usually uniformly dark reddish brown, almost black, the upper part sometimes a little darker than the lower, but with no sharp demarcation, as in *coloradensis;* vertex light brown, the antennal sockets margined behind with dark brown; pronotum with a wide median yellow stripe, and a thin median dark brown line; mesonotum and metanotum with a median yellow stripe; abdomen brown above. Fore wing: length (average), 9 mm.; width, 3.5 mm.; apex pointed; costal area much narrower basally than in *coloradensis;* membrane hyaline, markings brown consisting of numerous small spots; cross-veins margined; spot at gradate cross-vein between MP3+4 and Cu1 well developed. Hind wing: hyaline, without markings. The anal plates of male appear slender as seen in lateral view, and possess a long and slender terminal process directed ventrally; tenth sternite of moderate size, the aedeagus much shorter than in *coloradensis;* each "wing" of the tenth sternite gives rise to a slightly curved ventral process; parameres large, with a pair of long ventral arms and shorter dorsal ones. Ninth sternite of female not much longer than high; sclerotized plate of the eighth sternite about twice as long as broad, with a slightly concave posterior margin and with two lateral appendage-like arms (gonapophyses) attached to the middle of the plate and directed posteriorly.

Holotype (♀): Mt. Washington, New Hampshire; in the Museum of Comparative Zoology. Allotype, by present designation: Needham, Massachusetts, August 18 (A. P. Morse); in the Museum of Comparative Zoology.

Distribution: NOVA SCOTIA (Baddeck, Cape Breton Isl., June 15, G. Fairchild); QUEBEC (Alymer, June; Knowlton, June); ONTARIO (Biscotasing, August, September; Ottawa, August; Kearney, June; Arnprior, September; Vineland Sta., May); WISCONSIN (Rib Mts., St. Park, August 27); MANITOBA (Aweme, May, October); SASKATCHEWAN (Saskatoon, May); ALASKA (McKinley Peak, July 16, F. W. Morand; Bering Sea, Canadian Arctic Exped., July, 1913); MONTANA (Bitterroot Pass, July 29); IDAHO (Wallace, August 21); WYOMING (Laramie, July 5); COLORADO (Summit Co., July; Nederland, 10,000 ft., July, F. M. Carpen-

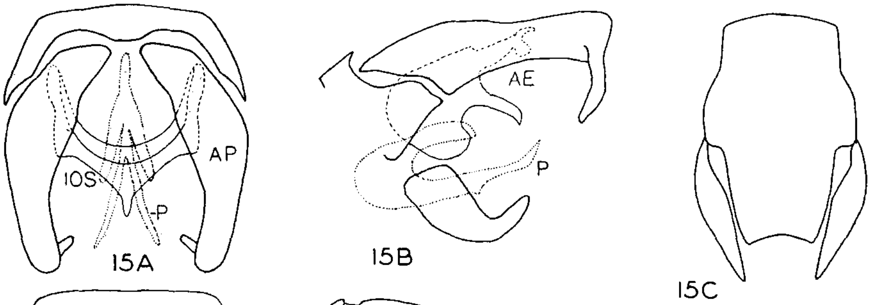

FIGURE 15. *Kimminsia disjuncta* (Banks). A, terminal abdominal segments of male (allotype), dorsal view; B, same, lateral view; C, eighth abdominal sternite of female (holotype) ventral view. Lettering as in figure 2.

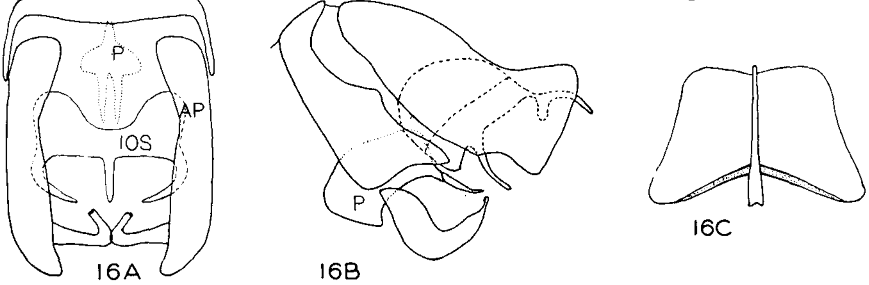

FIGURE 16. *Kimminsia coloradensis* (Banks). A, terminal abdominal segments of male (lectotype), dorsal view; B, same, lateral view; C, eighth abdominal sternite of female (allotype), dorsal view. Lettering as in figure 2.

ter; Wolf Creek Pass, July, C. Clagg); NORTH CAROLINA (Black Mts., Mt. Mitchell, September, N. Banks); NEW YORK (Axton, Adirondack Mts.; Catskill Mts., Greene Co.); NEW HAMPSHIRE (Mt. Washington); MASSACHUSETTS (Needham, Amherst, Cummington); MAINE (Mt. Katahdin, August).

This northern species resembles *coloradensis* and *involuta*, n. sp., in general appearance, but can be readily distinguished by body coloration, as indicated in the key. There are also slight wing differences, the costal area being narrower basally than that of *coloradensis* and the wing as a whole being more slender than that of *involuta*, n. sp. The genital structures of both sexes show marked differences from those of all other members of the genus. The eighth sternite of the female is surprisingly different from that of *coloradensis* in view of the similarity between the male genitalia of the two species. *Disjuncta* is much more common in Canada, especially in the eastern provinces, than it is in the United States, where it is quite rare outside of New England. Navas' *frostinus* was based upon a specimen from Framingham, Massachusetts. I have not seen the type, which was in Navas' collection, but the figure of the wing which accompanies the description, shows beyond doubt that the insect is *disjuncta*.

Kimminsia coloradensis (Banks)

Figure 16

Hemerobius coloradensis Banks, 1897, Trans. Amer. Ent. Soc., **24:** 26.
Boriomyia coloradensis Banks, 1905, ibid., **32:** 38.

Lower part of face light brown, upper part, below antennae and extending to about the level of the middle of the eyes, very dark reddish brown, the lower margin of this area being very sharply defined; space between antennae dark brown; sides of head below antennae light brown; vertex light brown, with a very thin median dark brown longitudinal stripe; antennal sockets margined with dark brown behind; pronotum with a wide median yellow or light brown stripe, bordered by dark brown and containing a very thin median dark brown stripe, continuing that of the vertex; on each side of this dark stripe there is usually a small spot of dark brown; mesonotum and metanotum with a prominent median light brown stripe, bordered by dark reddish brown; abdomen grey-brown. Fore wing: length (average), 9 mm.; width, 3.5 mm.; oval, apex broadly rounded, costal space very broad basally, widening abruptly from the base of the wing; veins dark brown, spotted; membrane hyaline; maculations consisting of numerous grey-brown spots; gradate veins strongly margined, and the points of origin of the branches of Rs and R1 + Rs are usually strongly marked with brown; the spot at the gradate vein between MP3 + 4 and Cu1 is usually darker than the others. Hind wing: hyaline, without markings. Anal plates of male broad in lateral view, each bearing a long, slender cylindrical process, terminating in a toothed head; these processes are directed towards the inner part of the segment, so they are usually not visible from the side; tenth sternite prominent, bearing a pair of slender, lateral, curved processes, extending ventrally and also bearing two flat lobes, extending dorsally; aedeagus short, about as long as the lateral process of the tenth sternite. Ninth sternite of the female small, semi-circular; eighth also very small and simple in structure, bearing a thin median process on its ventral surface, which widens slightly distally; this process is attached only to the anterior edge of the eighth sternite.

Types: Two cotypes, both from the same locality, Ft. Collins, Colorado (F. C. Baker), were mentioned by Banks after his description of the species, but I have been able to find only one of them in the Museum of Comparative Zoology. This is a male and it is here designated as the lectotype. Allotype, by present designation: Chimney Gulch, Golden, Colorado (Oslar); in the Museum of Comparative Zoology.

Distribution: CALIFORNIA (Bishop, Inyo Co., June 22, E. P. Van Duzee; Mono Lake, June 22, E. P. Van Duzee); OREGON (Crater Lake, July 19, E. P. Van Duzee); BRITISH COLUMBIA (Clinton, June; Hedley, July); ALBERTA (Lethbridge, September 11, J. H. Pepper); UTAH (Mirror Lake, Uinta Mts., 10,500 ft., August); COLORADO (Florissant; Leadville, July; Golden; Ft. Collins; Rocky Mt. Nat'l. Park; Pingree Park, 9000 ft., August; Saguache Co., July 10, R. H. Painter); WYOMING (Laramie, July 5, J. N. Knull).

This uncommon species has in the past been confused in collections with *disjuncta* Banks and *involuta*, n. sp. It differs from both of these in having a broader costal area basally and in having the dark brown markings on the face restricted to a definite band below the antennae. The anal plates of the male are like those of *involuta*, n. sp., but have the distal processes directed inwards, rather than ventrally; the aedeagus is much shorter than it is in *involuta*, n. sp. The eighth sternite of the female abdomen is exceptionally small and simple, not at all like that of *involuta*, n. sp., or *disjuncta*.

Kimminsia posticata (Banks)

Figure 17

Boriomyia posticata Banks, 1905, Trans. Amer. Ent. Soc., **32:** 39.

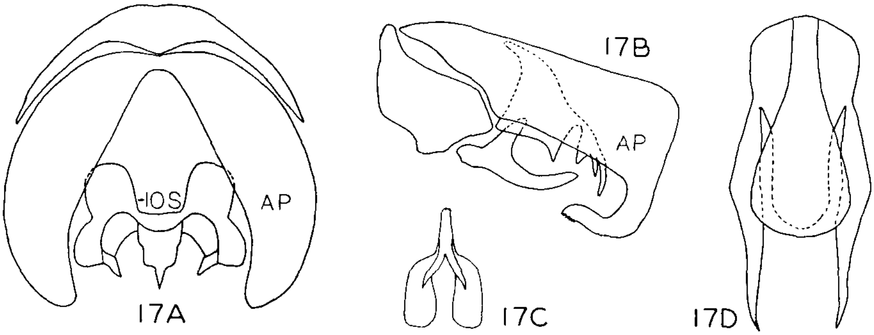

FIGURE 17. *Kimminsia posticata* (Banks). A, terminal abdominal segments of male (allotype), dorsal view; B, same, lateral view; C, parameres, dorsal view; D, eighth abdominal sternite of female (holotype), dorsal view. Lettering as in figure 2.

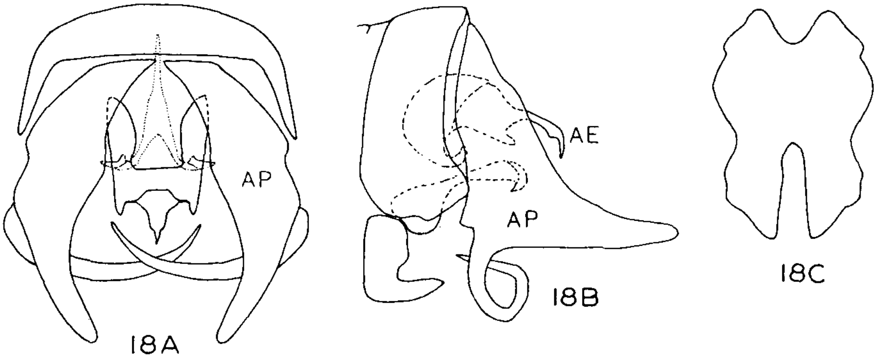

FIGURE 18. *Kimminsia furcata* (Banks). A, terminal abdominal segments of male (holotype), dorsal view; B, same, lateral view; C, eighth abdominal sternite of female (allotype), ventral view. Lettering as in figure 2.

Face with the upper part dark brown, the lower light brown, usually without sharp demarcation between the two areas; vertex light brown or yellow, pronotum with a wide median yellow stripe, containing a thin median dark stripe; mesonotum with a wide yellow stripe, but the anterior part of the yellow area contains a round, dark patch on each side of the median dark line, the spots usually being contiguous; also on posterior half of the mesonotum there is a dark brown spur-like process, extending into the yellow area from each side, the spur being curved and directed anteriorly; abdomen brown. Fore wing: length (average), 10 mm.; width, 4 mm.; rather slender for a species of Kimminsia, with a moderately wide costal area as in *disjuncta;* membrane hyaline; maculations very dark grey-brown, not very numerous but restricted to certain areas; spot around the gradate vein between MP3 + 4 and Cu1 very large and continued proximally by a series of maculations forming short stripes between Cu1 and the posterior margin; gradate veins margined; apical part of wing, distal of outer gradate veins containing many heavy and large maculations. Hind wing: usually slightly smoky posterior of Cu1 and anterior of MP1 + 2; no true maculations. Anal plates of male large and broad, as viewed from the side, terminating in a pair of long, curved processes, which are readily seen in a lateral view; tenth sternite complete, with a pair of posterior and a pair of anterior lobes; aedeagus appears serrate, seen from the side; parameres fused anteriorly, with two flat posterior plates and a pair of short pointed processes anteriorly. Ninth sternite of female rather long, nearly twice as long as wide; eighth sternite complex, consisting of three parts: a median flat plate, rounded posteriorly; a pair of elongate, pointed processes attached to the plate just anterior to the middle; and a median spatulate process attached to the anterior edge of the plate, the rest being free.

Holotype (♀): South Utah, July 1900; in the Museum of Comparative Zoology. Allotype, by present designation: Banff, Alberta, July 6, 1922 (C. B. D. Garrett); in the Canadian National Collection, Ottawa.

Distribution: UTAH (no other locality, July); COLORADO (Fairplay, July 11; Longs Peak, 9000 ft., July 12, 1926, E. C. Van Dyke); ALBERTA (Banff, July); NEW MEXICO (Red River, August 4, 1938, R. W. Kaiser; Colfax Co., August 21, 1927, R. H. Beamer); ARIZONA (Flagstaff, July 30, J. N. Knull).

This rare insect is the most strikingly marked of the Nearctic species of Kimminsia, the heavy markings along the posterior border of the fore wing being unique. The male genitalia are unusual in having a serrate aedeagus, and the eighth sternite of the female abdomen is remarkable for the broad median plate, apparently homologous with the slender one in *coloradensis*. Although I have seen only six specimens of this species, the localities listed above are widely scattered over the western part of the Nearctic region, so it is probable that the insect has a much more extensive range than is now indicated.

Kimminsia furcata (Banks)

Figure 18

Boriomyia furcata Banks, 1935, Psyche, **42**: 55.

Face nearly uniformly brown or very dark brown, at least to the clypeus; vertex brown, with a thin median darker stripe; pronotum with a wide median light brown stripe, traversed by a thin median longitudinal dark brown line, as in *coloradensis;* mesonotum with the brown area on the anterior part as in *involuta*, n. sp., though it is often somewhat divided medially; abdomen brown. Fore wing: length, 8–9 mm.; width, 3.5–4 mm.; apex slightly pointed; costal space as in *disjuncta;* maculations grey-brown, numerous, much as in *disjuncta;* spot at gradate vein between MP3 + 4 and Cu1 very heavy. Anal plates of male approximately triangular in shape, extended posteriorly into a slender, cylindrical lobe, and giving rise to a long and very slender process ventrally, which is strongly curved to the opposite side; tenth sternite small but complicated, with a pair of lateral, anterior, flat lobes; aedeagus long and slender; parameres fused anteriorly, but strongly divergent posteriorly. Ninth sternite of female large, but not long or tapering, with a small notch in the ventral margin near the apex; eighth sternite small, in the form of a heavy sclerotized plate with a deep incision in the posterior border and a shallow one in the anterior margin; teeth and hooks absent.

Holotype (♂): Argentine Pass, Colorado; (T. D. A. Cockerell); in the Museum of Comparative Zoology. Allotype, by present designation: Nordegg, Alberta, June 27, 1921 (J. McDunnough); in the Canadian National Collection.

Distribution: COLORADO (Argentine Pass); ALBERTA (Nordegg, June, July, 1921, 7 specimens; Lake Louise, July 16, 1938, G. S. Walley; Banff, August 17, 1927; Shovel Pass, Jasper Park, July 1, 1915).

This is apparently another uncommon species, but the seven specimens collected by Dr. McDunnough at Nordegg indicates that it may be locally common, at least. The holotype is the only specimen which I have seen outside of Alberta. The species resembles *involuta*, n. sp., in general appearance, but it is smaller and has a more conspicuous spot at the gradate vein between MP3 + 4 and Cu1. The male genitalia are very unusual in the possession of the long ventral processes on the anal plates; and the eighth sternite of the female abdomen is equally unusual for the absence of lateral hooks and for having an irregular outline.

Kimminsia involuta, n. sp.

Figure 19

Face usually uniformly brown or dark brown, occasionally the upper part slightly darker than the lower; vertex light brown, with a thin median dark stripe; pronotum with a wide median yellow stripe and a thin median dark brown line within the latter, as in *coloradensis;* mesonotum with a wide median yellow stripe, which encloses a conspicuous dark brown median patch on the anterior half of the notum; abdomen brown. Fore wing: length, 11 mm.; width, 5 mm.; broad, with a slightly rounded apex; costal area slightly broader basally than in *disjuncta*, but not so broad as in *coloradensis;* membrane hyaline, markings grey-brown, numerous, much as in *disjuncta;* spot at gradate vein between MP3 + 4 and Cu1 present but weak, not nearly so strong as in *disjuncta* or *furcata*. Anal plates of male broad, resembling those of *coloradensis* but with the distal process directed ventrally, so that it is easily visible from the side; tenth sternite large and complex, giving rise to a ventral, curved, posterior process; aedeagus long and slender; parameres complex, consisting of a flat basal piece, which is split and forked dorsally, and a pair of long, slender, dorsal, strongly curved processes. Ninth sternite of female long, fully twice as long as wide, as viewed from the side; eighth sternite long, the anterior half approximately square, the posterior half with convergent sides and an emarginate posterior border; attached to the sides of the sternite at about the middle are a pair of elongate, tooth-like processes, slenderly pointed, but very broad just beyond their bases.

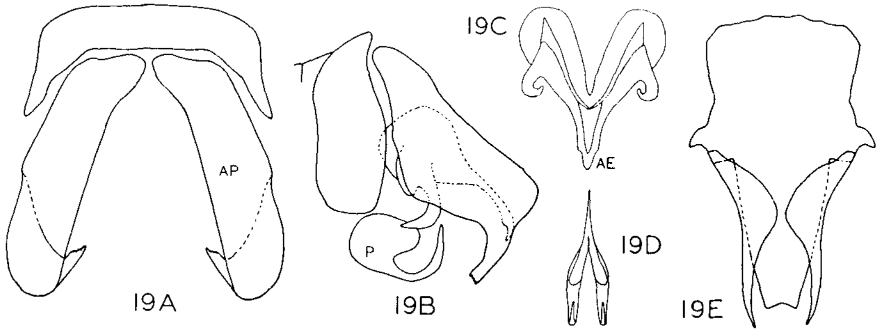

FIGURE 19. *Kimminsia involuta,* n. sp. A, terminal abdominal segments of male (holotype), dorsal view; B, same, lateral view; C, tenth sternite of same, dorsal view; D, parameres of same, dorsal view; E, eighth abdominal sternite of female (allotype), ventral view. Lettering as in figure 2.

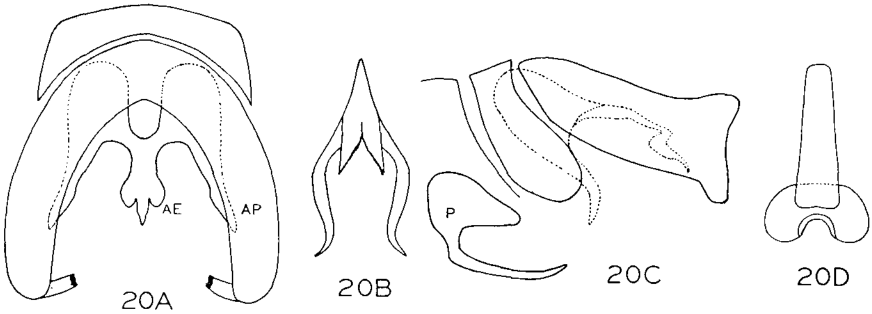

FIGURE 20. *Kimminsia longipennis* (Banks). A, terminal abdominal segments of male (allotype), dorsal view; B, parameres of same, dorsal view; C, terminal segments in lateral view; D, eighth abdominal sternite of female (holotype), dorsal view.

Holotype (♂): Rundle Mt., 5–7,000 ft., Banff, Alberta, June 25, 1924 (Owen Bryant); in the Museum of Comparative Zoology. Allotype: Banff, Alberta, July 17, 1925 (Owen Bryant); in the Museum of Comparative Zoology.

Paratypes: 1♂, Nordegg, Alberta, July 21, 1921 (J. McDunnough); 1♂, Nordegg, July 13; 1♂, Nordegg, July 3; 1♂, Nordegg, July 29; 1♂, Nordegg, June 30; 1♂, Nordegg, July 21; 1♀, Nordegg, July 14; 1♀, Nordegg, July 6; 1♂, Waterton, Alberta, July 10, 1923 (H. L. Seamans); 1♀, Hedley, British Columbia, July 23, 1923 (C. B. Garrett); 1♀, Banff, Alberta, August 24, 1922 (C. B. Garrett); 1♂, Kaslo, British Columbia, August 14, (R. P. Currie); 1♂, near Gilpin, July 29, 1934 (N. Dondelinger) all in the Museum of Comparative Zoology.—From Nordegg, Alberta, 1921 (J. McDunnough, collector): 1♂, June 15; 1♀, 1♂, June 17; 1♀, 1♂, June 27; 2♂, June 30; 1♀, June 22; 1♀, June 26; 1♂, July 3; 3♂, July 10; 1♂, July 12; 4♂, July 16; 1♀, July 13; 1♀, July 18; 1♀, July 29; 1♂, August 12; 1♂, Hope Summit, British Columbia, August 15, 1931 (A. N. Gartrell); 1♀, Banff, Alberta, August 4, 1922 (C. B. Garrett); 1♀, Hedley, British Columbia, June 28, 1927 (C. B. Garrett); 1♂, White Horse, Yukon, July–August, 1920 (A. P. Hawes); 1♀, Banff, August 5, 1925 (O. Bryant); 1♀, Waterton Lakes, Alberta, August 29, 1926 (K. M. King); all in the Canadian National Collection, Ottawa.—2♂, Longs Peak, Colorado, 9000 ft., July 12, 1926 (E. C. Van Dyke); in the California Academy of Sciences.—1 ♀, Banff, Alberta, July 17, 1915 (O. Bryant); 1 ♀, Banff, July 23, 1925 (O. Bryant); 1 ♂, Banff, August 5, 1925 (O. Bryant); 1 ♀, Laggan, Alberta, July 10, 1925 (O. Bryant); 1 ♂, Pingree Park, Colorado, August 14, 1934; all in R. C. Smith collection.—1 ♂, Kaslo, British Columbia, August 6 (R. P. Currie); 1 ♂, Kokanee Mt., British Columbia, August 10 (R. P. Currie); 1 ♀, Revelstoke, British Columbia, August 14 (R. P. Currie); all in the United States National Museum.—1 ♂, Wallace, Idaho, August 6, 1937 (O. Huelleman); 1 ♂, Yellowstone Nat'l. Park, Wyoming, July 30, 1933 (J. C. Jones); both in University of Minnesota collection.

Distribution: The exact localities at which this species has been collected are listed above; the general range of the insect, so far as known, is included in the three Canadian Provinces, Yukon, British Columbia, and Alberta; and the mountainous states, Idaho, Wyoming, and Colorado.

In the past this species has been confused with *coloradensis* and *disjuncta;* an examination of the material in the National Museum collection shows that the specimens recorded as *disjuncta* by Currie (1904b, p. 89) from British Columbia belong here. The wings are indeed very similar to those of the species mentioned, but do differ in shape and in the intensity of the maculations, especially of the spot at the gradate vein between MP3 + 4 and Cu1. The fore wing of *involuta* is proportionally broader than that of any other Nearctic Kimminsia, being only about twice as long as wide. The species may also be readily distinguished from *coloradensis* and *disjuncta* by the large median brown area on the mesonotum, this notum being entirely yellow in the other two species. The male genitalia are distinctive in the possession of the long aedeagus and complex ninth sternite; the eighth sternite of the female abdomen is unusually long, and is unique in having the long, lateral teeth.

Kimminsia longipennis (Banks)

Figure 20

Boriomyia longipennis Banks, 1920, Bull. Mus. Comp. Zool., **64:** 333.

Face yellow or very light brown, with numerous red specks and a larger red spot on the side of the head, just below the eye; antennae and legs yellow; vertex, pronotum and mesonotum uniformly yellow or very light brown, with scattered red specks; abdomen medium brown. Fore wing: length (average) 10 mm.; width, 3 mm.; slender, apex pointed, as in *disjuncta;* costal area rather narrow, as in the latter; veins light brown, spotted with widely separated red specks; membrane hyaline, only faint indications of light brown maculations; the only prominent spot is the one around the gradate vein between MP3 + 4 and Cu1. Hind wing: hyaline, no maculations. Anal plates of male of moderate size and width; distal process prominent, inwardly curved; tenth sternite large, the "wings" giving rise to a long curved process ventrally; aedeagus large and broad; parameres fused anteriorly, the free part forming a pair of sigmoidal arms. Ninth sternite of female only a little longer than wide, not prominent; eighth sternite with almost no sclerotization; at the posterior end of the sclerite there is a "U"-shaped ridge, attached to a very thin, semicircular membrane; anterior to this there is a broad, median flat plate, very weakly sclerotized, attached at its anterior border apparently to the edge of the preceding segment, but not attached to the semicircular plate mentioned.

Holotype (♀): Berkeley, California; April 1, 1915; in the Museum of Comparative Zoology. Allotype, by present designation: Leona Hts., California, August 27, 1908 (J. C. Bradley); in the Cornell University collection.

Distribution: This species has been taken so far only in California, but I have seen twenty-one specimens in addition to the types. These were collected at Carmel, May 19, 1913 (E. C. Van Dyke); Lompoc, July 22, August 6–8, 1935 (R. H. Beamer); Orange Co., July 14, 1929.

Longipennis is the palest of our species of Kimminsia. The reduced condition of the eighth sternite suggests that it is not at all closely related to our other species of the genus, though the broad median plate is doubtless the homologue of the similar structure in *disjuncta.* The wings and body of *longipennis* are unique in being marked with the red specks.

Kimminsia brunnea (Banks)

Figure 21

Boriomyia brunnea Banks, 1920, Bull. Mus. Comp. Zool., **64:** 333.

Face usually uniformly dark brown, rarely light reddish brown; vertex dark reddish brown; pronotum and mesonotum uniformly reddish or dark brown; occasionally with an indication of transverse dark markings on the pronotum, but never any sign of a median yellow stripe; abdomen brown, usually reddish. Fore wing: length, 9 mm.; width, 3.2 mm.; oval; costal area narrow at base and gradually broadened; membrane and veins brown, often with a reddish tint near or around pterostigma; no maculations except for a faint indication of dark brown at the gradate vein between MP3 + 4 and Cu1. Anal plates of male of moderate size and width; distal process reduced to a very short stub on inner side of the anal plates, and not visible from an exterior lateral view; tenth sternite complex, consisting of two large anterior lobes and a pair of small, slender posterior ones near the aedeagus; the latter long and slender, as seen from the side; parameres fused at the very anterior end, each consisting of a broad flat plate, terminating in a small, curved hook. Ninth sternite of female large but not very long, only about one and a half times as long as wide; eighth sternite large, consisting of (1) a flat plate, with parallel sides, except anteriorly where the plate widens and terminates in a shallowly incised margin; and (2) a pair of flat, broad plates near the posterior end.

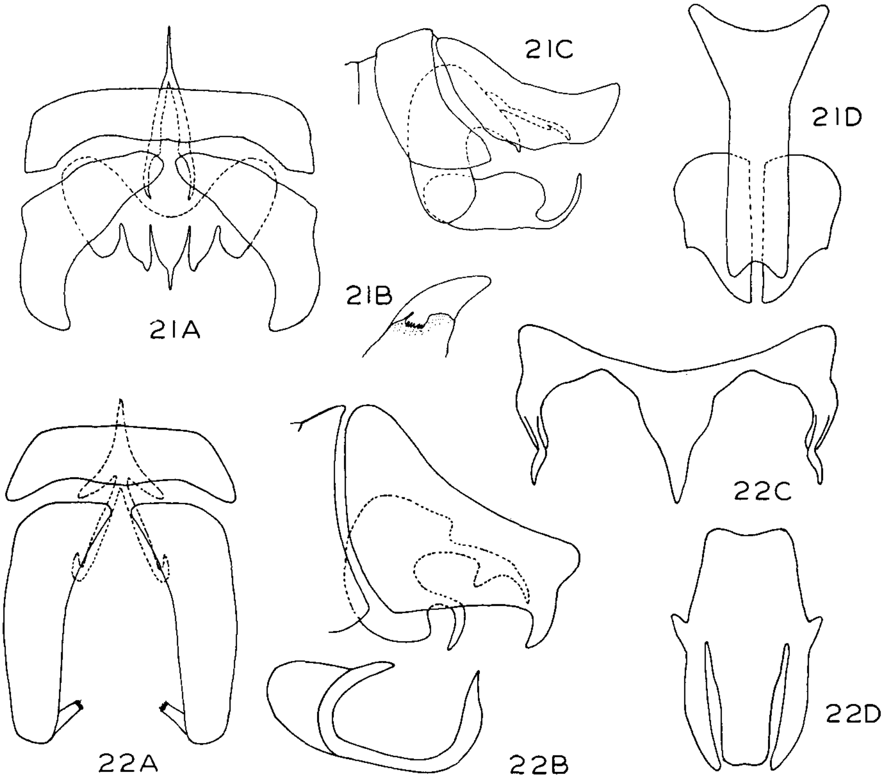

FIGURE 21. *Kimminsia brunnea* (Banks). A, terminal abdominal segments of male (allotype), dorsal view; B, tip of anal plate of same, inner view; C, terminal abdominal segments of same, lateral view; D, eighth abdominal sternite of female (holotype), dorsal view.

FIGURE 22. *Kimminsia pretiosa* (Banks). A, terminal abdominal segments of male (lectotype), dorsal view; B, same, lateral view; C, tenth sternite and aedeagus; D, eighth abdominal sternite of female, ventral view.

Holotype (♀): Midvale, Montana (C. E. Brown); in the Museum of Comparative Zoology. *Allotype*, by present designation: Ranger's Sta., Blue Riv. Valley, Summit Co., Colorado, 8211 ft., July 12 (C. S. Clagg) in the Museum of Comparative Zoology.

Distribution: ALBERTA (Moraine Lake, August 9, J. McDunnough); WASHINGTON (Paradise Valley, Ranier Nat'l. Park, July 17, E. C. Van Dyke); CALIFORNIA (Crabtree Meadow, Tulare Co., July 23, 1915, 10,550 ft.); COLORADO (Longs Peak, 9000 ft., June, July, E. C. Van Dyke; Pingree Park, August, R. H. and L. D. Beamer; Needle Mts., 11,900 ft., August 17, F. H. Knowlton; Sheephorn, Eagle Co., 7980 ft., August 11, C. S. Clagg; Mt. Manitou, June

21, E. C. Van Dyke; Blue River Valley, Summit Co., 8211 ft., August 12, C. S. Clagg); MONTANA (Midvale); WYOMING (Laramie, July 5, 1932, J. N. Knull; Centennial, July 2, 1931, J. N. Knull).

The uniformly brown wings of this species make it the most easily recognized species of Kimminsia in our fauna. The male genitalia are closest to those of *coloradensis,* but differ in many obvious details, such as the short distal process and the lobed tenth sternite. The 8th sternite of the female abdomen is unique in structure, but presumably the paired posterior plates are the homologues of the long, tooth-like structures in *disjuncta, involuta,* etc.

Kimminsia pretiosa (Banks)

Figure 22

Boriomyia pretiosa Banks, 1908, Trans. Amer. Ent. Soc., **34:** 260.

Face with the upper part from the antennae to about the level of middle of eyes, very dark brown; much lighter below; vertex medium brown; pronotum uniformly light brown or reddish brown, without dark lateral areas or median yellow stripe; mesonotum with the anterior border dark brown, almost black; rest of mesonotum light brown; abdomen dark brown. Fore wing: length (average), 7 mm.; width, 3 mm.; oval, apex round; costal area narrow basally, but very broad further distally, the point of greatest width being somewhat more distal than in other species of Kimminsia; membrane faintly brownish; veins brownish, spotted; maculations brown and faint, of uniform intensity, there being no heavy spot at the gradate vein between MP3 + 4 and Cu1; cross-veins only faintly margined. Hind wing: membrane hyaline, no maculations. Anal plates of male very broad, especially basally, terminating in a short distal process, directed ventrally; tenth sternite large, with a pair of broad lateral "wings," each having a posterior, curved process; aedeagus long and rather slender, with a short but prominent ventral tooth near the base; parameres large, coalesced anteriorly, forming two long curved posterior arms and a pair of much shorter ones dorsally. Ninth sternite of female about as broad as long; eighth sternite small, consisting of an elongate, approximately rectangular plate, with a pair of broad lateral processes arising near the middle.

Types: Five cotypes (3♀, 2♂) are in the Museum of Comparative Zoology, all from Golden, Colorado, July 22, 1907 (Oslar); one cotype (♂) from the same series is now in the Canadian National collection; and another cotype (♂) from Clear Creek, Colorado, is in the United States National Museum. One of the males from Golden, in the Museum of Comparative Zoology, is here designated the lectotype.

Distribution: COLORADO (Longs Peak, 9000 ft., July, E. C. Van Dyke; Golden, July; Boulder, October; Ft. Collins); ARIZONA (Williams, August 9; Flagstaff, July 27, 1936; Grand Canyon Nat'l. Park, July 13); OREGON (Antelope Mt., Harney Co., 5500 ft.); NEBRASKA (Pine Ridge, Dawes Co., July 8, L. Bruner).

This uncommon species and the following one (*schwarzi*) stand apart from all our other species of Kimminsia in lacking the yellow stripe and the dark brown sides of the pronotum. The wings of *pretiosa* are characterized by the uniformity of the maculations and the absence of the usually strong one at the gradate vein between MP3 + 4 and Cu1. Both male and female genitalia are very close to those of *schwarzi,* remarkably so, in view of the difference in wing markings.

Kimminsia schwarzi (Banks)

Figure 23

Hemerobius schwarzi Banks, 1903, Proc. Ent. Soc. Wash., **5:** 241.

Boriomyia schwarzi Banks, 1905, Trans. Amer. Ent. Soc., **32:** 38.

Boriomyia ultima Banks, 1930, Psyche, **37:** 223.

Face uniformly dark reddish brown or nearly so; vertex brown; pronotum usually uniformly light brown, rarely with a darker median area, but never with a median yellow stripe or dark lateral borders; mesonotum with dark brown anterior margin, otherwise uniformly light brown; abdomen dark brown. Fore wing: length (average), 8 mm.; width, 3.3 mm.; broadly oval, apex rounded; costal area not quite so narrow at the base as in *pretiosa* and not so wide at its greatest width; membrane hyaline or faintly yellow; veins spotted; markings dark brown; inner gradate veins strongly margined with brown, forming a distinct, transverse band; the outer gradate veins more faintly margined; m-cu and gradate vein below it strongly margined, forming a short, basal transverse band; usually another, but fainter transverse band is present between the inner gradate veins and the basal band. The anal plates of the male are large and very broad, terminating in a short, distal, ventral tooth; tenth sternite large, its "wings" having a prominent posterior process, strongly curved ventrally; aedeagus long, but very broad as viewed from above; parameres fused anteriorly, forming two long, slender posterior arms, strongly curved dorsally, and two, short, broad dorsal arms near the base of the others. Ninth sternite of female rounded, only a little longer than broad, as in *pretiosa;* eighth sternite small, with the rectangular plate incised anteriorly, and with a pair of lateral arms, as in *pretiosa.*

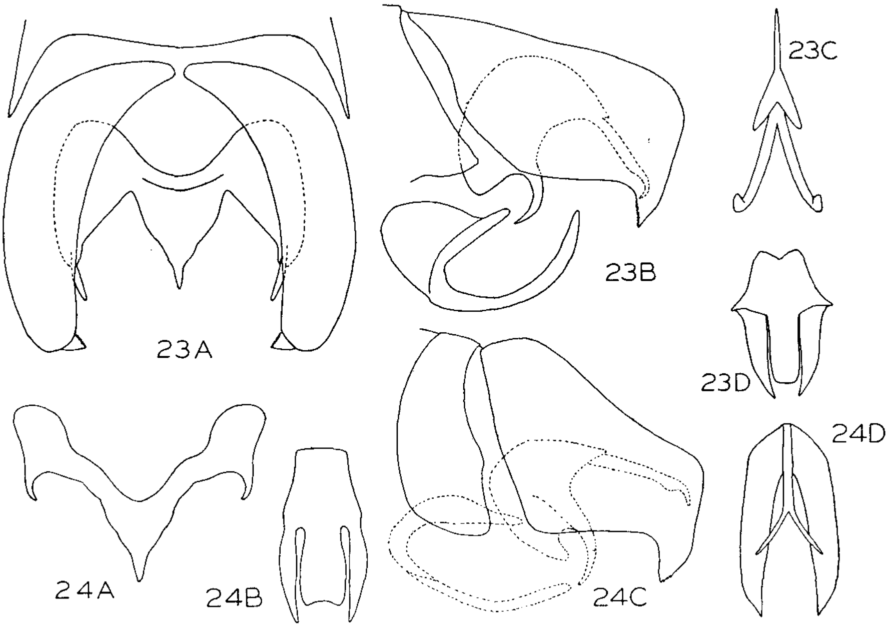

FIGURE 23. *Kimminsia schwarzi* (Banks). A, terminal abdominal segments of male (allotype), dorsal view; B, same, lateral view; C, parameres of same, dorsal view; D, eighth abdominal sternite of female (holotype), ventral view.

FIGURE 24. *Kimminsia fumata,* n. sp. A, tenth abdominal sternite of male (holotype), dorsal view; B, eighth abdominal sternite of female (allotype); C, terminal abdominal segments of male, lateral view; D, parameres of male, dorsal view.

Holotype (♀): Williams, Arizona, July 23; in the United States National Museum. Banks mentioned after his description paratypes from Mesilla, New Mexico. Two specimens (♂, ♀) from this locality are in the Museum of Comparative Zoology and bear the type labels. Of these specimens, the male is really the allotype, since it is the only type specimen of that sex.

Distribution: CALIFORNIA (Fallen Leaf Lake, Lake Tahoe, July 1, 14, 1915, E. C. Van Dyke; Gold Lake, Sierra Co., June 29, E. C. Van Dyke, Crabtree Meadow, Tulare Co., July, 10,550 ft.); ARIZONA (Williams, May, H. S. Barber); NEW MEXICO (Mesilla); COLORADO (Longs Peak, 9000 ft., July 12, E. C. Van Dyke).

This uncommon species, although obviously a close relative of *pretiosa,* differs from it in both body and wing characteristics, e. g., the wing markings, shape of the costal area, and the uniformly brown face. The male genitalia are surprisingly like those of *pretiosa,* but the aedeagus lacks the ventral tooth and is much broader, and the parameres are differently curved. The eighth sternite of the female abdomen is also very much like that of *pretiosa;* the only difference which seems at all obvious is the deep incision in the anterior border of *schwarzi,* this being absent in *pretiosa.* It may be, however, that a larger series of both species will indicate that this slight difference is individual, rather than specific.

I have placed *ultima* in synonymy with *schwarzi* on the basis of the eighth sternite of the female. The three type specimens of *schwarzi* are in very poor condition and there is slight indication of the markings on the wings. The eighth sternite of the female paratype of *schwarzi,* however, is identical with that of the holotype (♀) of *ultima.* All the other specimens of *schwarzi* which I have seen have the wing markings like those of the type of *ultima,* and among these there are two males whose genitalia are exactly like those of the allotype of *schwarzi*. I have therefore been led to the conclusion that the types of *schwarzi* have faded wings and that *ultima* is a synonym of that species. As Banks pointed out, the type of *ultima* possesses a median dark area on the pronotum; this is not visible in the types of *schwarzi*, but among the additional specimens which I have seen there are various degrees of intensity of darkening, so that this characteristic seems to be variable within the species.

Kimminsia fumata, n. sp.

Figure 24

Face uniformly dark brown, sometimes almost black; vertex also dark brown, at least anteriorly; pronotum uniformly medium brown, occasionally with a few darker spots, but never with a median yellow stripe; mesonotum uniformly medium brown, without a darker anterior border; abdomen brown. Fore wing: length (average), 8 mm.; width, 3.5 mm.; oval, apex rounded; costal area moderately wide, as in *schwarzi;* membrane smoky; veins brownish but spotted; markings brown, forming four transverse bands, as in *schwarzi,* though less distinct. Anal plates of male very broad but short, with a prominent, stout, distal tooth, extending ventrally; tenth sternite large, with small lateral "wings," bearing a long, curved, posterior process; aedeagus long and slender as seen from the side, without a ventral tooth; parameres fused basally, forming two flat posterior arms and two short, more slender ones above. Ninth sternite of female somewhat longer than broad; eighth small, the median piece deeply incised anteriorly, narrow posteriorly and bearing two broad, lateral arms extending posteriorly.

Holotype (♂): Longs Peak Inn, Boulder Co., Colorado, 9000 ft.; July 13, 1926 (E. C. Van Dyke). Allotype: same locality data, July 12; both in the California Academy of Sciences.

Paratypes: 2♀, same data as allotype, one in the California Academy of Sciences, the other in the Museum of Comparative Zoology.

This species is close to *schwarzi,* but differs in the smoky wings, absence of the dark anterior border of the mesonotum and details of genital structure. The male genitalia are like those of *schwarzi* in general form, but the anal plates are broader, and the posterior process on the "wings" of the tenth sternite are longer. The long arms of the parameres are much broader than in *schwarzi*. The eighth sternite of the female abdomen is very close to those of *schwarzi* and *pretiosa,* differences in the shape of the arms being slight.

Genus *Wesmaelius* Kruger

Wesmaelius Kruger, 1922, Stett. Ent. Zeit., **83:** 170; Killington, 1937, Monogr. Brit. Neuropt., **2:** 97.

Fore wing: oval; costal area abruptly broadened at base; recurrent humeral vein present; costal veinlets branched; usually three branches of Rs arising from R1 + Rs, sometimes two or four (not including MA); a strong cross-vein present between MA and MP1 + 2, just after the origin of the latter; a similar cross-vein present between MA and R5 at the latter's origin; two series of gradate veins, five or more cross-veins in the outer.

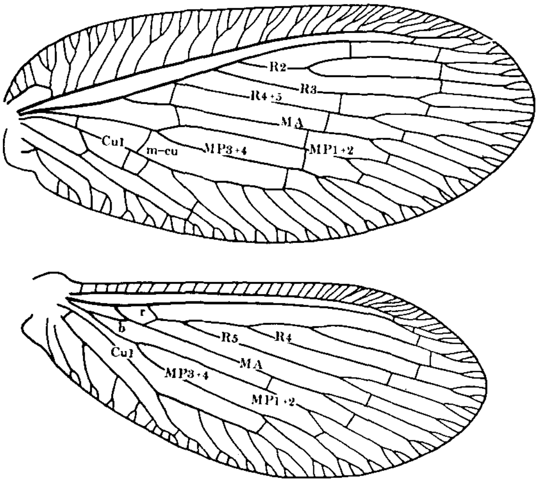

FIGURE 25. Wing venation of *Wesmaelius longifrons* (Walker). Lettering as in figure 1.

Hind wing: Rs coalescing with MA for a considerable distance; the cross-vein joining R1 to Rs is after the separation of MA from the latter; furcation of MP at about the level (or even proximal to) the separations of MA from Rs; two series of gradate veins, more than four cross-veins in the outer series.

Antennae slightly longer than the fore wing; prothorax broader than long, the lateral margins prolonged into a lobe. Anal plates of male triangular, with a heavily sclerotized ventral process, bearing teeth; tenth sternite with extensive "wings," each bearing a posterior process ventrally; aedeagus with a median plate; parameres fused anteriorly. Anal plates of female much smaller than the ninth sternite, which is elongate;

eighth sternite with a sclerotized median plate, as in Kimminsia.

Genotype: *Hemerobius concinnus* Stephens.

The life history of the single Nearctic species of the genus is entirely unknown. The egg and the larva of the British species are like those of Kimminsia and Hemerobius, except that the larval jaws are relatively longer (Killington).

Wesmaelius is at present known only from the Holarctic region and contains but one Nearctic species.

Wesmaelius longifrons (Walker)

Figures 25, 26

Hemerobius longifrons Walker, 1853, List Spec. Neuropt. Ins. Brit. Mus., **2:** 291.

Boriomyia longifrons Banks, 1905, Trans. Amer. Ent. Soc., **32:** 37.

Hemerobius alternatus Fitch, 1856, 1st & 2nd Rept. Ins. N. Y.: 93.

Hemerobius transversus Banks, 1904, Can. Ent., **36:** 61.

Allotomyia borealis Banks, 1935, Psyche, **42:** 56.

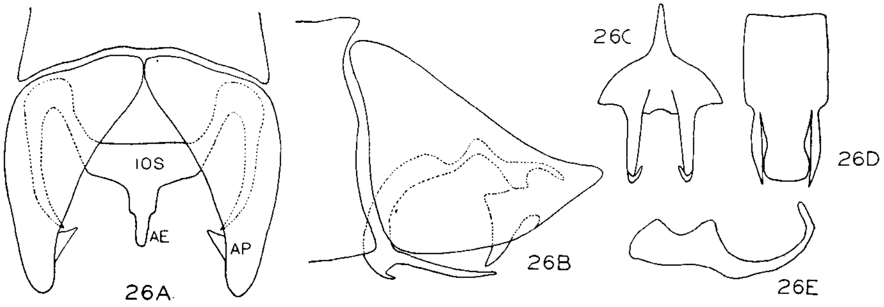

FIGURE 26. *Wesmaelius longifrons* (Walker). A, terminal abdominal segments of male, dorsal view; B, same, lateral view; C, parameres of same, dorsal view; D, eighth abdominal sternite of female, dorsal view; E, parameres of male, lateral view. Lettering as in figure 2.

Face uniformly dark brown, almost black; vertex usually yellow; pronotum with a very wide median light-brown stripe, bordered laterally by a thin margin of dark brown, or uniformly light brown without dark lateral margins; pronotum also usually with dark brown area along anterior border, except near the mid line; mesonotum either uniformly light brown, or with some dark brown laterally and along the anterior border; abdomen medium brown. Fore wing: length, 10 mm.; width, 5 mm.; broadly oval, usually, but very variable in shape, apex rounded; membrane hyaline, markings grey or grey-brown; cross-veins strongly margined, especially the inner gradates; the m-cu cross-vein and the one below it usually very strongly margined; the margination of the cross-veins forms either four nearly continuous bands across the wing, or eight (rarely six) short ones, the extent of the markings being variable. Anal plates of male large, triangular, with a distal, ventral process, appearing as a pointed tooth from a lateral view; tenth sternite large, "wings" slender, with a pair of long posterior arms; aedeagus short, with a blunt tooth below; parameres coalesced anteriorly, forming two long anterior, curved arms. Female with the ninth sternite elongate, triangular, fully twice as long as broad; eighth large, consisting of a flat median plate, bearing two lateral posterior arms.

Holotype (♂): St. Martin's Falls, Albany River, Ontario, Canada; in the British Museum. Allotype, by present designation: Covey Hill, Quebec, June 25; in the Museum of Comparative Zoology.

Distribution: NOVA SCOTIA; QUEBEC; ONTARIO; MANITOBA; SASKATCHEWAN (Indian Head); ALBERTA (Banff; Kananskis); BRITISH COLUMBIA (Hedley, Victoria); ALASKA (Savonoski, Naknek Lake); MAINE; NEW HAMPSHIRE; VERMONT; NEW YORK (Wells; Ithaca; Fulton Co.); MICHIGAN (Isle Royale; Douglass Lake); COLORADO (Sunset; Selkirk Mts.; Mt. Manitou; Estes Park; Gold Hill; Golden; Colorado Springs); WASHINGTON (Underwood); WYOMING (Teton Mts.; Wind River Range); UTAH (Logan; La Sal Mts.); OREGON (Mt. Hood; Haines); ARIZONA (Flagstaff; Williams; Grand Canyon). The adults have been collected from June through October.

This widely distributed species is a very distinctive one. It is the only Nearctic Hemerobiid possessing the basal cross-vein between R5 and MA near the origin of the latter, and the only one in which the cross-vein in the hind wing between Rs and R1 occurs after the first fork of Rs. The male and female genital structures are equally distinctive.

The type (♀) of Fitch's *alternatus* is in the Museum of Comparative Zoology and an examination of its genital and wing structure shows that it is a synonym of *longifrons*, as it has been recognized by Banks in the past. The type (♂) of *transversus* Banks, which is in the same museum, is likewise this species; the wings have more extensive bands than most specimens, but as I have previously pointed out the wing markings are unusually variable in this species. *Allotmyia borealis* Banks was based upon a damaged male of *longifrons;* this has already been noted by the author of the species on a label attached to the type in the Museum of Comparative Zoology.

Genus *Sympherobius* Banks[11]

Sympherobius Banks, 1904, Proc. Ent. Soc. Wash., **6:** 209; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 40; Killington, 1937, Monogr. Brit. Neuropt., **2:** 111.

Palmobius Needham, 1905, Bull. N. Y. State Mus., **86:** 17.

Spadobius Needham, 1905, ibid.: 16.

Niremberge Navas, 1909, Rev. R. Acad. Cienc. Madrid, **7:** 377.

Eurobius Kruger, 1922, Stett. Ent. Zeit., **83:** 171.

Fore wing: usually slenderly oval; costal area either narrow or broad, not usually abruptly widened at base; recurrent humeral vein present; costal veinlets forked; one or two branches of Rs arising from stem R1 + Rs (not including MA); R4 + 5 usually coalesced with MA for a considerable distance basally; MP connected by a cross-vein to MA shortly after the former's origin; two series of gradate veins, four or less in outer series.

Hind wing: MA usually having slight contact with Rs or joined to it by a cross-vein; basal cross-vein between R1 and Rs beyond the separation of MA from Rs (or connecting cross-vein) and far proximal to origin of R4 + 5; furcation of MP distal of separation of MA from Rs (or connecting vein); not more than two outer gradate veins, often none; only one or two in the inner gradate series.

Anal plates of male with at least one distal process; tenth tergite with elongate "wings" and a single median plate of the aedeagus, which has a complicated form; ninth tergite with a conspicuous ventral extension of the posterior border; parameres nearly completely fused; ninth sternite triangular, often elongate. Anal plates of female small; ninth tergite enlarged ventrally.

Genotype: *Hemerobius amiculus* Fitch.

The egg of the species of this genus is minutely sculptured, like that of Hemerobius. The larva is relatively shorter and broader than that of Hemerobius; the third antennal segment is very short and broadened basally. The life history of two Nearctic species is known: *S. amiculus* Fitch (Smith, 1923) and *S. barberi* Banks (Smith, 1934).

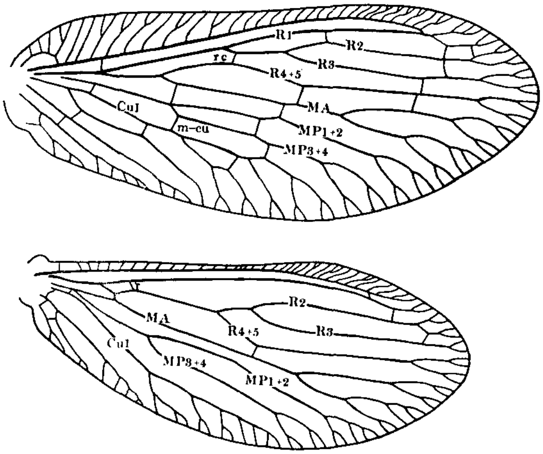

FIGURE 27. Wing venation of *Sympherobius amiculus* (Fitch). rc, radial cross-vein; other lettering as in figure 1.

Several attempts have been made to divide Sympherobius into two or more genera. Navas and Krüger, noting that in some species the first branch of Rs (R4 + 5) was coalesced with MA and in others arose directly from R1 + Rs, proposed a splitting of the genus on this difference. Although it is true that among the individuals of certain species one of these two types of radial sectors predominates, in other species both types occur with nearly equal frequency. This venational difference cannot, therefore, be satisfactorily used as the basis of generic separation. Needham's genus Spadobius was based upon a single specimen of *S. amiculus* having an adventitious cross-vein between R1 and R4 + 5 near the origin of the latter. Such adventitious veins occur commonly in all Hemerobiidae and certainly have no specific value. Some venational characteristics, however, are sufficiently constant in our Nearctic species of Sympherobius to be of taxonomic use.

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[11] The generic synonymy given here includes only that involving the Nearctic species.

Best of these is the cross-vein, termed the radial cross-vein, present in some species between R4 + 5 and some part of Rs above. In a number of species this vein is completely absent (e.g., *barberi*); in others it connects R4 + 5 with R2 + 3 (e.g., *umbratus*); and in others it connects R4 + 5 to R1 + Rs before the origin of R2 + 3 (e.g., *occidentalis*). The presence or absence and the position of this cross-vein are surprisingly stable. I have found them to hold constant in all but about two per cent of the Nearctic specimens, and in most species I have seen no exceptions. The shape of the wing is also of much taxonomic value, some species having a broad costal area (e.g., *barberi*) and others having this space very narrow (e.g., *angustus*). Although the color of the body is nearly the same in all species, the color of the fore wings differs so greatly between many species that in spite of some individual variation, it has much taxonomic value. The male genitalia furnish the most significant specific structures. The shape and the number of the processes on the anal plates are remarkably constant, and these can usually be examined without relaxing or dissection of the abdomen. The ninth sternite of the male abdomen and the parameres also exhibit excellent specific differences. The terminal abdominal segments of the female are so much alike that I have found them of no use in distinguishing the species.

Sympherobius occurs in Europe, Asia and North and South America. The genus is especially well represented in the Nearctic region, which includes the fifteen species considered below and probably several others still unknown. These Nearctic Sympherobius, unlike members of the other genera of Hemerobiidae, are most abundant in the southern part of the region, and many of the species are confined to the southern states.

KEY TO THE NEARCTIC SPECIES OF SYMPHEROBIUS

1. Radial cross-vein present in fore wing.........2
   Radial cross-vein absent......................9
2. Fore wing with all cells either margined with dark brown or filled with dark brown and margined with hyaline membrane..............3
   Fore wing without such markings; the membrane hyaline and spotted with gray or brown.....5
3. Costal area of the fore wing narrow
   gracilis, n. sp. (p. 231)
   Costal area of the fore wing broad............4
4. First fork of Cu1 at a point far distal of the cross-vein m-cu; radial cross-vein between R4 + 5 and R1 + Rs, before the origin of R2 + 3 ....*occidentalis* Fitch (p. 230)
   First fork of Cu1 at the level of the m-cu cross-vein; radial cross-vein between R4 + 5 and R2 + 3.............*umbratus* Banks (p. 230)
5. Radial cross-vein of fore wing between R4 + 5 and R2 + 3................*amiculus* Fitch (p. 228)
   Radial cross-vein of fore wing between R4 + 5 and R1 + Rs, before the origin of R2 + 3...6
6. Costal area of fore wing broad
   californicus Banks (p. 232)
   Costal area narrow..........................7
7. Veins of fore wing nearly uniformly brown
   similis, n. sp. (p. 236)
   Veins of fore wing with conspicuous brown and white markings..........................8
8. Large species, fore wing over 6 mm. long; mesonotum yellow medially, with a large black spot on each side..........*angustus* Banks (p. 233)
   Small species, fore wing about 4 mm. long; mesonotum nearly uniformly brown, only slightly darker laterally than medially
   bifasciatus Banks (p. 233)
9. Fore wing membrane predominately brown, hyaline area in form of small spots
   arizonicus Banks (p. 234)
   Fore wing membrane predominately hyaline...10
10. Fore wing maculations forming three distinct bands across the central part of the wing
    pictus Banks (p. 234)
    Fore wing maculations in the form of small, irregular spots, distributed more or less uniformly over the wing...........................11
11. Costal area of the fore wing broad
    barberi Banks (p. 235)
    Costal area of the fore wing narrow.........12
12. Fore wing very slender, inner gradate veins widely separated.......*perparvus* McLachlan (p. 236)
    Fore wing at most only moderately slender, the two upper and the two lower gradate veins close together...........................13
13. Veins of fore wing uniformly brown, maculations diffuse...............*distinctus*, n. sp. (p. 238)
    Veins of fore wing spotted with brown and white; maculations few..........................14
14. Fore wing membrane hyaline
    killingtoni, n. sp. (p. 238)
    Fore wing membrane yellow
    limbus, n. sp. (p. 236)

Sympherobius amiculus (Fitch)

Figures 27, 28

Hemerobius amiculus Fitch, 1856, 1st & 2nd Rept. Ins. N. Y.: 95.

Sympherobius amiculus Banks, 1904, Proc. Ent. Soc. Wash., **6**: 209; 1905, Trans. Amer. Ent. Soc., **32**: 42.

Sympherobius buenoi Navas, 1912, Broteria, **10**: 198, fig. 7a; 1914, Bull. Brook. Ent. Soc., **9**: 20.

Head medium to dark brown, shiny; pronotum medium brown, dull, usually slightly mottled with grey; antennae slender, the basal third dark grey, the rest light brown; legs yellowish. Fore wing: length, 3.5 mm.; width, 1.3–2 mm.; broad, apex usually rounded but sometimes nearly pointed; costal space rather broad, nearly as in *barberi;* wing membrane usually hyaline, but sometimes the brown maculations are so diffuse that the membrane appears nearly uniformly brown; veins often light and marked with dark brown spots, one of these being at the base of each microtrichium; maculations mostly grey-brown, sometimes yellow-brown; inner gradate veins very dark brown, often very heavily and widely margined, especially those of the posterior part of the wing; at least the two upper and two lower inner gradates close together; radial cross-vein between R4 + 5 and R2 + 3. Hind wing hyaline, no maculations. Anal plates of male large, each with three posterior processes, two lateral and one more nearly median, the latter being very short and more curved than the other two; tenth sternite large, with the "wings" slightly flattened, but slender; aedeagus very prominent, curved anteriorly over the tenth tergite (anal plates); parameres coalesced anteriorly, but separating posteriorly to form a pair of flattened, irregular plates; ninth tergite with only a short posterior projection from the ventral border.

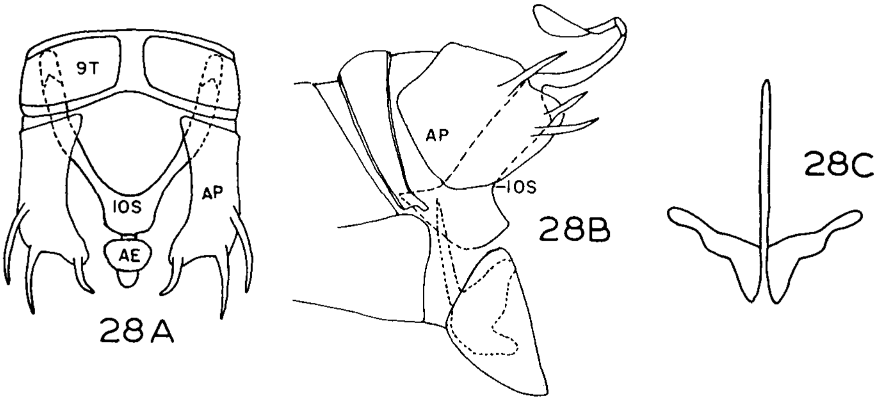

FIGURE 28. *Sympherobius amiculus* (Fitch). A, terminal abdominal segments of male (allotype), dorsal view; B. same, lateral view; C. parameres of same, dorsal view. Lettering as in figure 2.

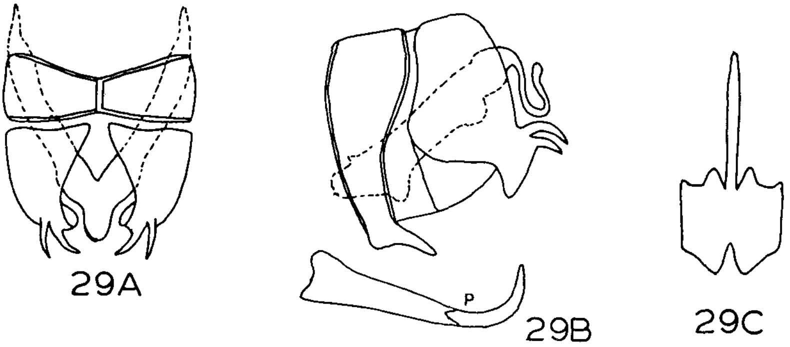

FIGURE 29. *Sympherobius occidentalis* (Fitch). A, terminal abdominal segments of male, dorsal view; B, same, lateral view; C, parameres of same, dorsal view. Lettering as in figure 2.

Holotype (♀): in the Museum of Comparative Zoology. This specimen bears no locality data, but Fitch states in his description that specimens were taken in New York and Illinois, so that the type was undoubtedly collected in one of those states. Allotype, by present designation: Cambridge, Massachusetts, July 13 (F. M. Hull); in the Museum of Comparative Zoology.

Distribution: Although this species probably occurs in the eastern United States and Canada as far west as Oklahoma and Nebraska, the actual records show a very spotted distribution. I have seen specimens from various localities in the following states and provinces: Nova Scotia, Ontario, New Hampshire, Vermont, Massachusetts, New York, Ohio, Illinois, West Virginia, Virginia, North

Carolina, Georgia, Florida, Arkansas (Washington Co.), Louisiana, Nebraska (Lincoln), Kansas, Michigan (E. Lansing), Wisconsin (Brule), Minnesota (Benn, Eveleth), Oklahoma (Roff, Parson, El Reno, Cheyenne, Okemah, Pearson), and Texas (Galveston). Most of the adults have been collected during June and July, but a few have been taken in March, April, May, August and early September.

This is one of our two species of Sympherobius having the radial cross-vein between R4 + 5 and R2 + 3, the other being the very distinctive *umbratus*. The wing markings are exceptionally variable in *amiculus*. In some specimens the membrane is very light, while in others it is decidedly light brown, as a result of the more generally diffuse maculations. The heavy brown maculations near the fork of Cu1a are always present, though in some they extend much further forwards than in most. In spite of the variation in wing markings and wing shape, the position of the radial cross-vein is constant, so far as the origin of R2 + 3 is concerned, and this enables easy recognition of the species. The anal plates of the male also furnish distinctive characteristics in the form and arrangement of the three posterior processes.

Navas' *buenoi*, from White Plains, New York, is without doubt this species. Although Navas stated that the specimen was like *umbratus*, his figure shows that the type is nothing more than *amiculus*. It is very doubtful that he had a specimen of *umbratus* for comparison, since this is an extremely rare species.

Sympherobius umbratus (Banks)

Figure 30

Hemerobius umbratus Banks, 1903, Proc. Ent. Soc. Wash., **5**: 242.
Sympherobius umbratus Banks, 1905, Trans. Amer. Ent. Soc., **32**: 41.

Head uniformly dark brown; antennae light brown; pronotum and mesonotum and abdomen uniformly medium brown. Fore wing: length, 5 mm.; width, 2.5 mm.; broadly oval; costal area wide, as in *barberi;* radial cross-vein between R4 + 5 and R2 + 3; wing membrane almost uniformly brown, except that all veins are narrowly margined by a hyaline strip; the brown area in each cell thus formed is margined by slightly darker brown; gradate veins normally arranged, with the two upper and two lower ones close together. Hind wing: very nearly hyaline, with only a faint trace of brown. Anal plates of male with three processes, the lateral one being smoothly curved, the other two being at least slightly furcate. The detailed structure of the tenth sternite has not been determined.

Holotype (♂): Williams, Arizona, June 10; in the United States National Museum.

In addition to the type specimen, I have seen only a broken female, from Albuquerque, New Mexico (Oslar). This was mentioned by Banks at the time of his description of the species. Apparently the insect has not been collected subsequently.

This is a very distinct insect. In general appearance it resembles *occidentalis* and *gracilis*, n. sp., but differs in the uniformity of the brown on the wing membrane, the broader costal area, the position of the radial cross-vein, the color of the body, and in the genital structure, at least in the form of the processes on the anal plates of the male.

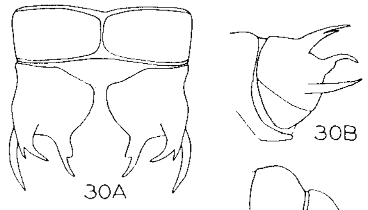

FIGURE 30. *Sympherobius umbratus* Banks. A, terminal abdominal segments of male (holotype), dorsal view; B, same, lateral view.

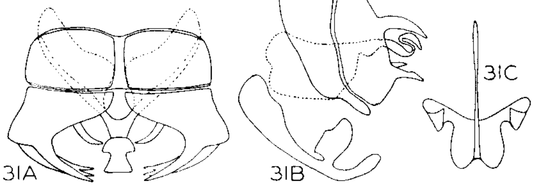

FIGURE 31. *Sympherobius gracilis*, n. sp. A, terminal abdominal segments of male (holotype), dorsal view; B, lateral view; C, parameres of same, dorsal view.

Sympherobius occidentalis (Fitch)

Figure 29; plate 1, figure 10

Hemerobius occidentalis Fitch, 1856, 1st & 2nd Rept. Ins. N. Y.: 95; Hagen, 1861, Synop. Neuropt. N. A.: 201.
Sympherobius occidentalis Banks, 1905, Trans. Amer. Ent. Soc., **32**: 40.

Face black, shiny; vertex medium or dark brown, nearly black, the rest light brown or yellow; pronotum with a very thin light median stripe bordered laterally by a wide dark brown stripe on each side, this in turn margined laterally with yellow; mesonotum with a continuation of the median yellow stripe of the pronotum, and with a "V" formed by the converging of the extensions of the lateral borders of the pronotum; metanotum and abdomen dark brown to medium brown. Fore wing: length, 5 mm.; width, 2 mm.; moderately broad; costal area not quite so broad as in *amiculus;* radial cross-vein connected to R1 + Rs before the origin of R2 + 3; branches of Cu1 arranged so that they are mostly parallel to MP and the branches of Rs; membrane brownish, veins dark brown; cells of wing margined by a heavy dark brown border; cross-veins conspicuously margined with dark brown; a very dark brown patch at the inner angle of wing. Hind wing: membrane smoky, maculations absent. Anal plates of male small, with two short, strongly curved posterior processes; tenth sternite large, the two "wings" very long, extending well into the eighth segment; aedeagus broad, short; parameres coalesced anteriorly, forming a pair of broad, flat plates posteriorly.

Types: Fitch apparently had only one specimen of this species, collected at the Henderson River, Illinois (probably in Henderson County). This specimen seems to have been lost, for it is not in the Museum of Comparative Zoology or the United States National Museum. Fortunately, the insect is a very distinctive one, and Fitch's description enables us to recognize the species almost without question. There are but three Nearctic species of Sympherobius known to me which possess the peculiar margination of the cells mentioned by Fitch. One of these has been collected in Arkansas and Kansas, where it is not uncommon; a second, described below as *gracilis,* is known only from North Carolina; the third, *umbratus* Banks, has been found only in Arizona and New Mexico. These three species differ in various characteristics not mentioned by Fitch (body color, wing venation, genital structure). Of these species it seems far more probable that the first, from Kansas, is *occidentalis,* which was described from Illinois. It is on the basis of that interpretation that I have redescribed the species here.[12] I do not consider it advisable, however, to designate a neotype of *occidentalis* until other Illinois specimens have been found. Curiously enough, although I have examined many hundreds of specimens of Hemerobiids from Illinois, chiefly collected by Dr. Ross and his associates, I have found no specimens of *occidentalis* among them.

Distribution: ILLINOIS (Henderson River, October); KANSAS (Onaga; Manhattan, August 8, R. C. Smith); ARKANSAS (Washington Co., July 23, 1938); DISTRICT OF COLUMBIA (Washington, according to Hagen's identification); TEXAS (College Sta., June 23, 1938, R. H. Beamer).

This rare species resembles the following (*gracilis,* n. sp.) but the thorax of the latter is uniformly brown, not marked with yellow, and there are numerous venational and other wing differences. There is also a slight resemblance to *umbratus* Banks, but the wing markings are not very similar. The distal processes on the anal plates are very short, more so than in any of the other Nearctic Sympherobius.

Sympherobius gracilis, n. sp.

Figure 31

Face dark reddish brown, vertex much lighter reddish brown; pronotum and mesonotum uniformly dark brown; abdomen dark brown. Fore wing: length, 5 mm.; width, 2 mm.; narrow, costal space narrow, nearly as in *angustus;* membrane hyaline, but with the hyaline area restricted to a narrow strip on each side of all veins; cells of the wings filled with dark brown, as in *umbratus* though the margin of the brown area is darker than the inner part, giving much the appearance of the wing of *occidentalis;* radial cross-vein just at origin of R2 + 3 in the type, but that is probably not its normal position; Cu1 forked nearly to m-cu; veins nearly uniform brown, not spotted. Anal plates of male with three distal processes, the lower lateral one furcate at tip; tenth sternite large, the "wings" very much expanded; parameres also large, the separated portions forming a complicated and gracefully curved spatulate plate.

Holotype (♂): Raleigh, North Carolina, June 11, 1934 (R. R. Leiby); in the Museum of Comparative Zoology. The female is unknown.

This striking species resembles *umbratus* in general appearance, but it has a more slender wing and a narrower costal area. The male genitalia also are very distinctive; only one of the processes on the anal plates is furcate, instead of two, as in *umbratus*.

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[12] Hagen (1861) recorded a specimen of *occidentalis* from Washington, D. C., pointing out that the antennae of his specimen were longer than those described by Fitch, who stated that in the type the antennae were shorter than the body and all black. The antennae of Fitch's specimen were undoubtedly broken, for they are longer than the body in all other species of Sympherobius, and in some species they are black for only about a third of their length.

Sympherobius californicus Banks

Figures 32; plate 2, figure 12

Sympherobius californicus Banks, 1911, Trans. Amer. Ent. Soc., **37:** 346.

Head medium to light brown, clypeus often darker brown; vertex usually light brown, never black or very dark brown; pronotum with a distinct median yellow stripe bordered laterally with dark brown; mesonotum usually medium yellow-brown, somewhat variegated; abdomen medium brown. Fore wing: length, 5 mm.; width, 2.5 mm.; broadly oval, costal space broad, but not so broad as in *barberi;* radial cross-vein short, between R4 + 5 and R2 + 3; membrane hyaline or slightly brownish; cross-veins and Cu1 strongly margined with dark brown; sometimes also branches of Cu1 and not infrequently other veins are irregularly spotted with dark brown. Hind wing: hyaline, maculations absent. Anal plates of male with three distal processes, the lateral one being smoothly curved, the middle one long but straight, and the inner one very small and straight; tenth sternite large, with a distinct tooth-like projection visible in side view just below the aedeagus; ninth tergite with a very long posterior extension ventrally; parameres much as in *amiculus.*

Types: Banks mentioned three types of this species: "From Los Angeles, Claremont, and Pasadena, California." I have been able to locate only two of these types, one (♂) from Pasadena (J. Grinnell) and the other (♂) from Claremont (Baker); both are in the Museum of Comparative Zoology. An examination of the genital structure of these shows that the specimen from Claremont is really *barberi* Banks (1903). The other specimen, from Pasadena, is therefore now designated the lectotype of *californicus.* Since this is a male and no female type has been established, a female from Bericia, California, in the Museum of Comparative Zoology, is now designated the allotype.

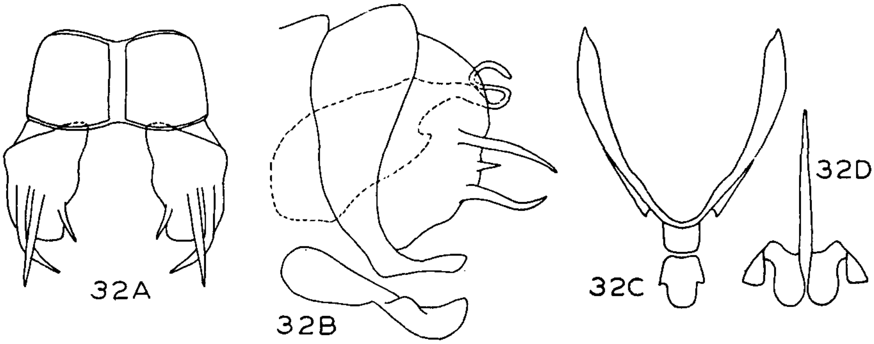


FIGURE 32. *Sympherobius californicus* Banks. A, terminal abdominal segments of male (lectotype), dorsal view; B, lateral view; C, tenth sternite of same, dorsal view; D, parameres of same, dorsal view.

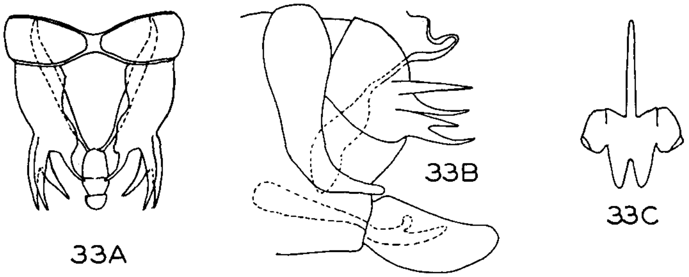


FIGURE 33. *Sympherobius bifasciatus* Banks. A, terminal abdominal segments of male (holotype), dorsal view; B, same, lateral view; C, parameres of same, dorsal view.

Distribution: CALIFORNIA (Pasadena, Bericia, Berkeley, Laguna Beach, Claremont, San Francisco, San Mateo Co., Placer Co., Carmel, Fresno, Alameda, Santa Barbara, Mt. View, Alhambra, Richmond, Ventura, Ramona, Leona Hts.). The adults have been collected from March to November. The species appears to be confined to California, but it is hardly uncommon there, for I have seen at least sixty specimens.

Californicus resembles *barberi* and *angustus* in certain respects. The radial cross-vein is present in *californicus* and is situated like that in *angustus*, but the costal area and the wing as a whole is broad, as in *barberi*. The male genitalia are closest to those of *barberi*, which has the outer process of the anal plates strongly twisted, instead of smoothly curved, as in *californicus*.

Sympherobius bifasciatus Banks

Figure 33

Sympherobius bifasciatus Banks, 1911, Trans. Amer. Ent. Soc., **37:** 347.

Head with light brown face, the lower part not darker than medium yellowish brown; vertex light brown; antennae light brown; pronotum with a fairly wide median yellow stripe, bordered laterally by brown, usually not very dark; mesonotum yellow medially, with dark brown laterally; abdomen brown. Fore wing: length, 3.7 mm.; width, 1.6 mm.; narrow, but slightly broader than in *angustus;* membrane hyaline; costal space narrow, as in *angustus;* maculations light brown; cross-veins, Cu1 and its branches, Cu2 and the anals strongly margined with brown, not quite so dark as in *angustus;* marginations around gradate veins broadly diffuse, forming two transverse bands; radial cross-vein between R4 + 5 and R1 + Rs, before the origin of R2 + 3. Anal plates of male with three distal processes, all long, the lower one deeply forked; ninth sternite with a long posterior prolongation ventrally; tenth sternite small with rather slender "wings"; parameres as in *angustus*.

Holotype (♂): "Colorado" (G. F. Baker); in the Museum of Comparative Zoology.

Distribution: COLORADO (no further data); ALBERTA (Lethbridge, June 10, 1926, J. E. Revell; and June 18, 1929, J. H. Pepper).

This small species, which is apparently very rare, resembles *angustus* closely in wing and body markings; it may be distinguished from the latter by the lighter brown of the wing marginations, and the lighter color of the head, as well as by the male genitalia. The anal plates of *bifasciatus* are very unusual in possessing a deeply forked process.

Sympherobius angustus (Banks)

Figure 34; plate 2, figure 16

Hemerobius angustus Banks, 1904, Trans. Amer. Ent. Soc., **30:** 102.
Sympherobius angustus Banks, 1905, ibid., **32:** 41.
Sympherobius tristis Navas, 1914, Bull. Brook. Ent. Soc., **9:** 15, fig. 2.

Head with face dark brown, almost black; in some specimens the upper part of the face is dark reddish brown, but at least the lower part is nearly black; vertex dark brown or black; antennae dark, grey-brown; pronotum with a thin, median yellow stripe, bordered by dark brown laterally; abdomen dark brown. Fore wing: length, 6.5 mm.; width, 2.8 mm.; slender, with a very narrow costal area; membrane hyaline; almost all veins margined with dark brown, especially the cross-veins, Cu1 and its branches, Cu2 and the anals; in some specimens the maculations around the gradate veins are unusually wide and diffuse, giving the appearance of two bands across the wing as in *bifasciatus;* radial cross-vein between R4 + 5 and R1 + Rs, before the origin of R2 +3, as in *californicus*. Anal plates of male with four distal processes, all strongly curved, including the very short one; ninth sternite with a prominent anterior extension ventrally; tenth sternite small, with broader "wings" than in *californicus;* parameres as in the latter, but with a shorter fused portion.

Types: Banks indicated the cotypes of this species as follows: "One specimen from Mesilla, N. Mex. (A. P. Morse), and others from Las Vegas Hot Springs, August (Barber and Schwarz)." The specimen from Mesilla, a female, is in the Museum of Comparative Zoology, and it is here designated the lectotype. One specimen, also a female, from the Las Vegas locality is in the United States National Museum. Allotype, by present designation: Pingree Park, Colorado, August 12, 1926 (R. C. Smith); in the Museum of Comparative Zoology.

Distribution: UTAH (Manila, August 11, G. F. Knowlton, F. C. Harmston); NEW MEXICO (Las Vegas, Mesilla, Santa Fe); COLORADO (Longs Peak, 9000 ft., July, E. C. Van Dyke; Golden, July; Pingree Park, August); BRITISH COLUMBIA (100 Mi. House, June).

This rare species is the largest and most striking of our Sympherobius. It is close to the smaller *bifasciatus* in wing markings and general body structure, but the male genitalia are decidedly different in the two insects, especially in the form of the distal processes on the anal plates.

Navas' *tristis*, from Pecos, New Mexico, is clearly *angustus*. Navas himself stated that this insect resembled *angustus*, but did not mention characteristics distinguishing the two. The wing, as he has

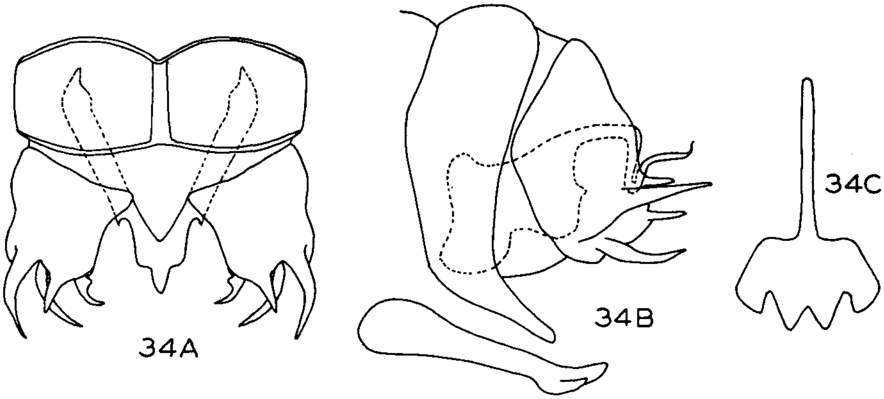


FIGURE 34. *Sympherobius angustus* Banks. A, terminal abdominal segments of male (allotype), dorsal view; B, lateral view; C, parameres of same, dorsal view.

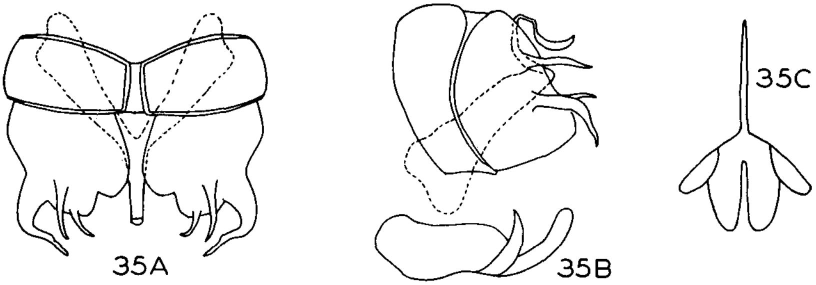


FIGURE 35. *Sympherobius barberi* Banks, A, terminal abdominal segments of male (allotype), dorsal view; B, same, lateral view; C, parameres of same, dorsal view.

drawn it, is broader than that of *angustus,* but his figures are usually incorrectly proportioned. The wing markings, the narrow costal area, and the venation are typical of *angustus.*

Sympherobius arizonicus Banks

Plate 2, figure 14

Sympherobius arizonicus Banks, 1911, Trans. Amer. Ent. Soc., **37:** 346.

Face dark brown, somewhat reddish, except for a lighter area below antennae; the antennae, thorax and abdomen dark reddish brown. Fore wing: length, 4.5 mm.; width, 2 mm.; costal area narrow, but broader than in *killingtoni,* n. sp.; in the type the wing membrane is so nearly covered with brown maculations that the wing as a whole is nearly uniformly brown, except for numerous, evenly distributed hyaline spots; two lower inner gradate veins not darker than the others; inner gradates normally arranged, the two lower and two upper close together; radial cross-vein absent. Hind wing: slightly brownish. The male is unknown.

Holotype (♀): Prescott, Arizona (Oslar); in the Museum of Comparative Zoology.

This strikingly marked species I have not been able to recognize in any of the collections of Sympherobius which have been sent to me. It is possible that the type is only a very heavily marked specimen of the species which I have described below as *killingtoni,* but none of the numerous individuals of the latter which I have seen even approach the type of *arizonicus* in wing markings.

Sympherobius pictus (Banks)

Plate 2, figure 13

Hemerobius pictus Banks, 1904, Can. Ent., **36:** 62.
Sympherobius pictus Banks, 1905, Trans. Amer. Ent. Soc., **32:** 41.

Face light or medium brown; vertex dark brown; antennae grey; thorax and abdomen dark brown. Fore wing: length, 5 mm.; width, 2 mm.; broadly oval; costal area narrow, as in *arizonicus;* membrane hyaline; distal half of wing conspicuously bordered by a series of extensive light brown maculations, not quite contiguous; four conspicuous dark brown bands extend transversely over the middle part of the wing, one at the level of the outer gradates, one at the level of the two upper inner gradates, one at the level of the two lower inner gradates, and one at the level of the forking of MP; radial cross-vein absent; inner gradates normally arranged, the two upper and the two lower ones close together; because of the oval shape of the wing, the inner gradate veins seem nearer to the base of the wing than they do in *arizonicus* or *killingtoni*. The male is unknown.

Types: Two females (cotypes) from "south western" Colorado (Oslar) are in the Museum of Comparative Zoology; one of these has been now labelled the lectotype.

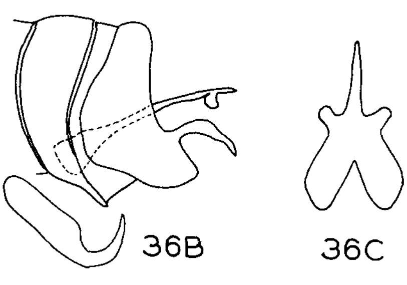


FIGURE 36. *Sympherobius perparvus* (McLach.). A, terminal abdominal segments of male, dorsal view; B, same, lateral view; C, parameres, dorsal view.

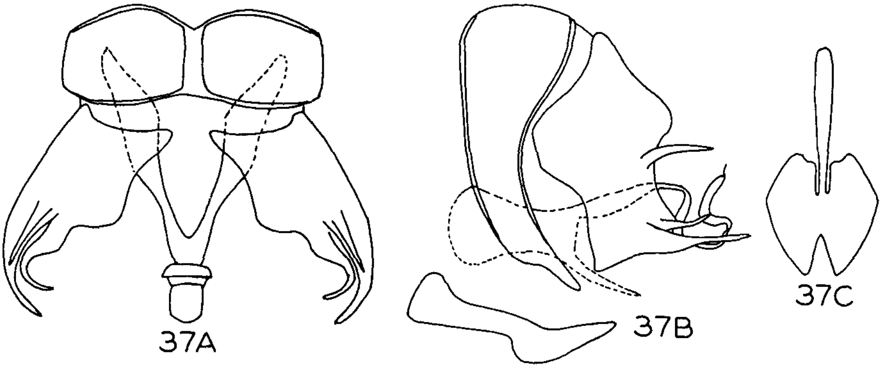


FIGURE 37. *Sympherobius distinctus,* n. sp. A, terminal abdominal segments of male (holotype), dorsal view; B, same, lateral view; C, parameres of same, dorsal view.

In addition to the types, I have seen only one other specimen of *pictus,* that also being a female; it was collected near Saguache, Colorado, August 10, 1937, by R. H. Painter, and is in Dr. R. C. Smith's collection.

The fore wings of this species are marked in a unique manner, so far as our Nearctic species are concerned. There is a slight possibility that this is the same insect as *killingtoni,* n. sp., the three individuals mentioned above being in this case abnormally marked. However, I have seen no specimens of *killingtoni* with markings in any way resembling even faintly those of the types of *pictus.*

Sympherobius barberi (Banks)

Figure 35; plate 1, figure 9

Hemerobius barberi Banks, 1903, Proc. Ent. Soc. Wash., **5:** 241.

Sympherobius barberi Banks, 1905, Trans. Amer. Ent. Soc., **32:** 42.

Face light reddish to light yellowish brown; vertex with some dark brown over eyes; pronotum with a light brown stripe, bordered by darker brown, this being distinctly spotted; mesonotum usually uniformly reddish brown; abdomen dark or medium brown. Fore wing: length, 4.5 mm.; width, 2 mm.; broadly oval, with a very broad costal space; radial cross-vein absent; membrane hyaline, with numerous irregular light brown maculations; a dark brown patch near the end of Cu1 and at the inner angle of wing; cross-veins not margined usually, rarely very faintly. Anal plates of male with three distal processes, the outer lateral one being strongly curved and in most specimens strongly twisted; the inner process is very short and the dorsal one is only a little longer than this; tenth sternite moderate in size, with somewhat broader "wings"; parameres as in *californicus*, with a shorter fused portion.

Types: two females (cotypes) from Williams, Arizona, July 20 and 21 (H. S. Barber and E. A. Schwarz); in the United States National Museum. Allotype, by present designation: Tucson, Arizona, December 19, 1934 (L. P. Wehrle); in the Museum of Comparative Zoology.

Distribution: CALIFORNIA (Ft. Yuma, Imperial Co.; Alpine, San Diego Co.; Cloverdale, Sanomo Co.; Susanville, Larsen Co.; Pleyto, Monterey Co.; Ventura; Campo; Indio; San Jacinto Mts., Redding; Claremont; Santa Paula; Mt. Wilson; Alhambra); OREGON (Colestin, Jackson Co.); COLORADO (Sloss; Glenwood Springs); ARIZONA (Maricopa, Pinal Co.; Patagonia; Santa Rita Mts.; Cochise Co.; Yarnell; Tucson; Huachuca Mts.); NEW MEXICO (Mesilla); UTAH (Klags Sta., Davis Co.; Pintura); TEXAS (Brownsville; Devil's River; Sutton Co.; Karnes Co.; Calvert; Galveston); OKLAHOMA (Grandfield; Page; Pearson; Oswalt; Big Cedar; Lebanon; Tuskahoma); KANSAS (Manhattan; Wichita); ARKANSAS (Washington Co.); FLORIDA (Cedar Keys; Jacksonville, Tampa); SOUTH CAROLINA (Charleston); VIRGINIA (Falls Church); OHIO (Summit Co.); NORTH CAROLINA (no further data); PENNSYLVANIA (no further data). The adults have been collected during all months of the year, though they seem to be most abundant during the summer months.

This is the commonest southern species of the genus. It is similar to *amiculus* in appearance, but differs in the lack of the radial cross-vein in the fore wing, as well as in many details of genital structure. The inner and dorsal processes of the anal plates are very short. In all specimens of *barberi* which I have seen from the area west of Oklahoma and Kansas, the outer process of the anal plates is distinctly twisted, but in specimens from the more eastern states, this process is hardly twisted at all. There seems, therefore, to be some geographic factor envolved here, but I have been unable to detect any other characteristics which are correlated with the one mentioned.

Dr. L. P. Wehrle has sent me a fine series of this species which he has bred in the laboratory; the larvae fed on the mealy bug, *Lantana camara* var. *mista.*

Sympherobius limbus, n. sp.

Figure 38

Face light reddish brown, clypeus darkened; vertex pronotum, mesonotum and abdomen nearly uniformly reddish brown, only slightly darker laterally than medially; antennae grey-brown. Fore wing: length, 3.4 mm.; width, 1.3 mm.; moderately slender; costal area narrow, as in *angustus;* membrane yellow; inner and outer gradates margined with large brown spots, mostly faint; radial cross-vein absent. Anal plates of male with three processes, the outer very large, stout, and only slightly curved, the inner-ventral one short and very strongly curved, and the dorsal one short and straight; tenth sternite with a prominent ventral process extending posteriorly from each "wing"; parameres with the fused part forming a spatulate head, with a conspicuously fringed margin.

The female is unknown.

Holotype (♂): Alpine, Texas. July 1, 1928, (R. H. Beamer); in the University of Kansas Museum.

This small Sympherobius resembles *killingtoni* in general habitus, but can be distinguished by the yellow wings. The male genitalia are unusual in having the posterior process on the tenth sternite and especially the fringed border on the parameres, a characteristic which I have not seen in any other members of the genus.

Sympherobius similis, n. sp.

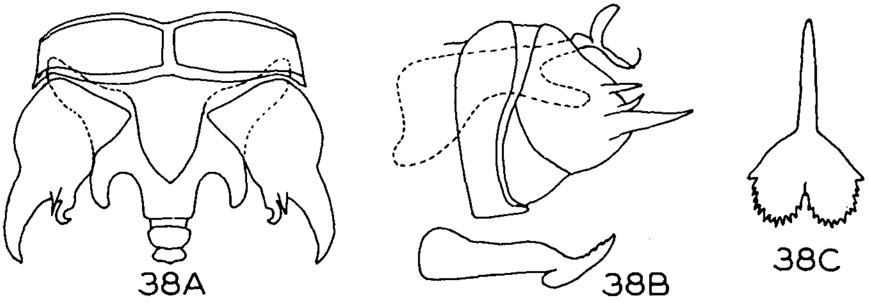
Figure 39

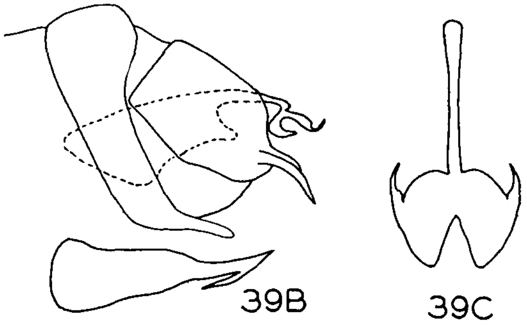
Face yellow; vertex yellow-brown, with some dark brown laterally; pronotum and mesonotum with a median yellow, longitudinal stripe, bordered laterally with dark brown; first antennal segment yellow, others dark brown; abdomen yellow-brown. Fore wing: length, 3.5 mm.; width, 1.8 mm.; moderately slender, much as in *angustus;* costal area narrow as in the latter; membrane smoky, with faint and scattered brown maculations; Cu1 as far as m-cu, Cu2, and most cross-veins strongly margined with dark brown; radial cross-vein present between R4 + 5 and R1 + Rs, before origin of R2 + 3; inner gradates close together, normally arranged. Anal plates of male with two processes, the outer one stout and strongly curved, the inner one small and nearly parallel with the other; tenth sternite with broad "wings," each bearing a small posterior tooth; parameres small, the fused part forming a spatulate head, with a pair of anterior projections.

The female is unknown.

Holotype (♂): Santa Rita Mountains, Arizona, July 17, 1932 (R. H. Beamer); in the University of Kansas Museum.

This small species resembles *bifasciatus* Banks. The wings of *similis* are somewhat broader than





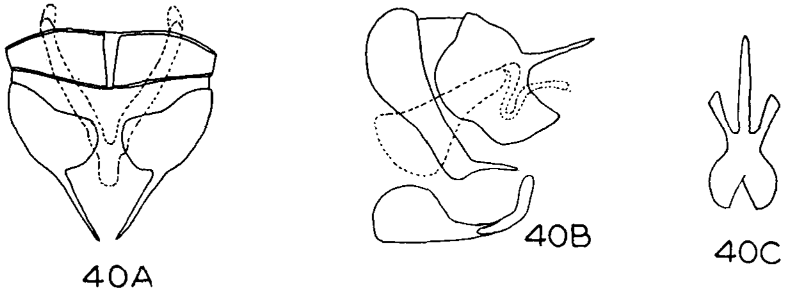


FIGURE 38. *Sympherobius limbus,* n. sp. A, terminal abdominal segments of male (holotype), dorsal view; B, same, lateral view; C, parameres of same, dorsal view.

FIGURE 39. *Sympherobius similis,* n. sp. A, terminal abdominal segments of male (holotype), dorsal view; B, same, lateral view; C, parameres of same, dorsal view.

FIGURE 40. *Sympherobius killingtoni,* n. sp. A, terminal abdominal segments of male (holotype), dorsal view; B, same, lateral view; C, parameres of same, dorsal view.

those of *bifasciatus* and possess brown veins which are very nearly uniformly colored, not interrupted with white, as in *bifasciatus.* The male genitalia are very different from those of the latter, having only two unforked processes on the anal plates.

Sympherobius perparvus (McLachlan)

Figure 36; plate 2, figure 15

Hemerobius perparvus McLachlan, 1869, Ent. Mo. Mag., **6:** 22.

Sympherobius perparvus Banks, 1905, Trans. Amer. Ent. Soc., **32:** 41.

Sympherobius sparsus Banks, 1911, Trans. Amer. Ent. Soc., **37:** 346.

Face pale brown, often slightly reddish; vertex usually somewhat darker brown; pronotum and mesonotum brown or dark brown, variegated; antennae dark grey-brown; abdomen brown, often dark brown. Fore wing: length, 4 mm.; width, 1.5 mm.; slender; costal margin narrow; membrane hyaline; maculations grey, usually rather large but widely scattered; gradate veins and longitudinal veins not margined; as a result of the slenderness of the wing the branches of Rs are much longer than in the other Nearctic species of Sympherobius; radial cross-vein absent; inner gradate veins widely separated, forming a fairly even series. Anal plates of male with an elongate but very slender posterior projection ventrally;

tenth sternite rather small, the "wings" not greatly expanded; parameres small, the fused part broad as viewed from the side, the separated parts forming two spatulate plates, strongly curved, as viewed laterally.

Types: Three specimens (2♀, 1♂) from Bosque Co., Texas (G. W. Belfrage); in the British Museum.

Distribution: CALIFORNIA (Bishop; Indio; Little Lake, Inyo Co.); ARIZONA (Patagonia; Wilcox; Washington Mts., near Nogales); NEW MEXICO (Mesilla; Vaughn); COLORADO (Boulder, London); TEXAS (Bosque Co.; Jackson Co.; Potter Co.); OKLAHOMA (Lugert; Roff; Oswalt); KANSAS (Manhattan; Wichita; Stafford Co.; St. Frances; Ellsworth; Dickerson Co.); SASKATCHEWAN (Saskatoon, July 26, K. M. King). The adults have been collected from May through September.

This is the smallest and palest of the Nearctic Sympherobius. It differs from all others in the elongate fore wing and the widely separated gradate veins. The male genitalia are closest to those of *killingtoni,* n. sp., both species having the single process on the anal plates. In *perparvus,* however, this process is strongly curved, whereas it is perfectly straight in *killingtoni.*

Banks' *sparsus* was based upon a female from Kansas (type in the Museum of Comparative Zoology) which unquestionably is *perparvus;* the widely spaced inner gradates were mentioned by Banks in his description. Although I have not been able to examine the types of *perparvus* at the British Museum, the McLachlan collection having been received there shortly after my visit to the museum in 1938, Mr. D. E. Kimmins kindly compared specimens which I sent to him with the types. All of the latter possess the venational and other wing characteristics of the species described here as *perparvus.*

Sympherobius distinctus, n. sp.

Figure 37

Face very dark red-brown; vertex, pronotum, mesonotum somewhat lighter; metanotum apparently with a median yellow stripe; abdomen dark brown. Fore wing: length 6.5 mm.; width, 2.5 mm.; broad, but costal space narrow; veins uniformly dark brown, not spotted; membrane of wing mostly hyaline, but irregular brownish maculations are very abundant and are very diffuse along the posterior margin; gradate veins not margined; inner gradate veins normally arranged, the upper two and the lower two close together; radial cross-vein absent. Anal plates of male with three terminal processes, the inner one being broad basally and very strongly curved distally; tenth sternite small, but distinctive, possessing a long posterior process on each of the "wings"; parameres with the spatulate head of other Sympherobius, but lacking the twisted lobation present in other Nearctic species.

Holotype (♂): Pingree Park, Colorado; August 18, 1926 (R. C. Smith); in the Museum of Comparative Zoology.

This is a very unusually marked species. The uniformly brown wings of *distinctus* are found elsewhere only in *gracilis, occidentalis* and *umbratus,* all of which have differently arranged markings, the maculations coinciding with the cells of the wing. *Distinctus* is probably closer to *arizonicus* than to any other members of the genus, at least so far as wing structure is concerned; but it has larger hyaline areas on the wing and the veins are uniformly brown. The male genitalia are unique in having the long posterior process on the "wings" of the tenth sternite.

Sympherobius killingtoni, n. sp.

Figure 40; plate 2, figure 11

Face from light to dark brown; vertex dark brown; antennae grey; pronotum and mesonotum dark brown, often reddish; abdomen dark brown. Fore wing: length (average), 4.5 mm.; width, 2 mm.; moderately broad, but with narrow costal space; wing membrane hyaline, maculations usually greyish brown or light brown and evenly distributed; inner gradate veins normally arranged, not widely separated, the two upper ones and the two lower ones close together and dark brown; radial cross-vein absent; cross-veins usually margined, and in many specimens the inner gradates (especially the lower two) are widely and heavily margined with dark brown. Anal plates of male with a single distal process, this being straight, not curved as in *perparvus;* ninth tergite with a slender posterior projection ventrally, as in *perparvus;* tenth sternite with broad "wings"; parameres similar to those of *perparvus,* but with a smaller, spatulate head, and long oblique processes extending anteriorly.

Holotype (♂): Eureka, Utah, August 13 (T. Spaulding); in the Museum of Comparative Zoology. Allotype, same locality data, August 15; in the Museum of Comparative Zoology.

Paratypes: 1♂, Mesilla, New Mexico; 2♂, Eureka, Utah, August 13 (Spaulding); 1♂, same, August 14; 1♂, Williams, Arizona, May 28; 1♂, Globe, Arizona, August 10 (Parker); 1♂, Tucson, Arizona, June 7, 1934 (A. A. Nichol); 3♂, 1♀, Tooele, Utah, August 29, 1937 (L. L. Hansen); 1♂, Logan, Utah, August 29, 1937 (L. L. Hansen); all in the Museum of Comparative Zoology.—1♀, Logan, Utah, July 6, 1937 (H. F. Knowlton); 1♀, Trout Creek, Utah, July 25, 1937 (H. B. Stafford); 1♀, Las Vegas, New Mexico, August 4 (H. S. Barber); 1♀, Kamos, Utah, June 24, 1936 (F. C. Harmston); 1♂, Williams, Arizona (H. S. Barber); 1♂, Dallas, Texas, March 6, 1909 (F. S. Tucker); 1♀, Tooele, Utah, August 29, 1937 (L. L. Hansen); all in the United States National Museum.—2♀, Independence, California, June 13, 1929 (R. L. Usinger); 1♂, 1♀, El Paso, Texas, March 25, 1937 (J. O. Martin); 1♀, Maricopa, Pinal Co., Arizona, October 17, 1927 (J. A. Kusche); all in the California Academy of Sciences.—1♀, Flagstaff, Arizona, July 30, 1928 (D. J. and J. N. Knull); in the Ohio State University Museum.—1♀, Torrance Co., New Mexico, July, 1925 (C. H. Martin); in the University of Kansas Museum.

Distribution: CALIFORNIA (Independence, Needles, Bishop); ARIZONA (Flagstaff, Washington Mts., Tucson, Florence, Maricopa, Globe); UTAH (Eureka, Richfield, Logan, Tooele, Kamos); IDAHO (Hansen, Hubbs, Butte); NEW MEXICO (Las Vegas); TEXAS (El Paso, Dallas). The adults have been collected from March through October.

This species has been confused with *perparvus* in the past. It differs from the latter in having broader and more heavily marked wings and in having the inner gradate veins normally arranged, i.e., the two upper and two lower gradates of the fore wing are close together, as in all Nearctic Sympherobius except *perparvus*. The male genitalia are close to those of *perparvus*, but the process of the anal plates is straight, not curved as in the latter. I had at first thought that *killingtoni* might be *arizonicus* Banks, the type of which is a unique female; but the wing markings of this type are so very different from that which I have seen in the long series of *killingtoni* that the possibility of such an identity seems extremely slight. There is a similar remote chance that *killingtoni* is *pictus* Banks, known only from the two female types and one additional female, but here again the wing markings of the known specimens of *pictus* are strikingly different from those of all the *killingtoni* which I have seen.

This insect has been named for Dr. F. J. Killington, of Southhampton, England, whose recent "Monograph of the British Neuroptera" is unquestionably destined to become one of the classics of entomological literature.

Genus *Megalomus* Rambur

Megalomus Rambur, 1842, Hist. Nat. Ins. Neuropt.: 418; Killington, 1937, Monogr. Brit. Neuropt., **2:** 131.

Fore wing: usually broadly oval, costal space very wide and abruptly broadened at base; recurrent humeral vein present; costal veinlets forked; four or more branches of Rs (very rarely three) usually arising from stem R1 + Rs (not including MA); basal piece of MA either absent, or present at the very base of the wing; a cross-vein present between MA and MP1 + 2, considerably beyond the origin of the latter; two series of gradate veins, the outer forming a curved line (usually) which is for the most part parallel with the outer margin of the wing; more than ten gradate veins usually present in the outer series.

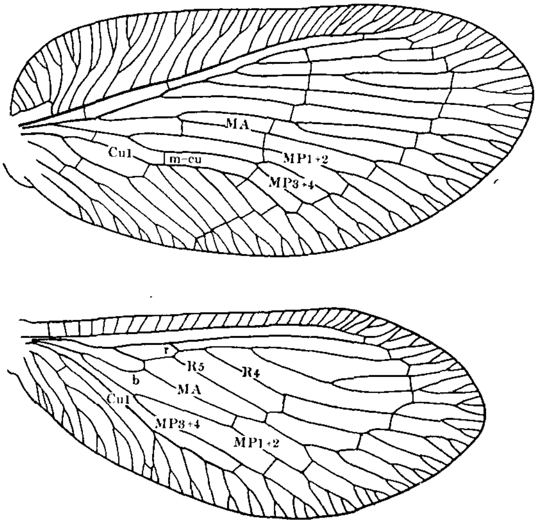


FIGURE 41. Wing venation of *Megalomus moestus* Banks. Lettering as in figure 1.

Hind wing: MA coalesced with Rs for a very short distance or connected with it by a cross-vein (usually); cross-vein between R1 and Rs close to the point of separation of MA from Rs, usually slightly distal to it; Rs with three or four main forks, very rarely two; basal piece of MA usually curved; furcation of MP at the level of or distal to separation of MA from Rs; two series of gradate veins, five or more in the outer series.

Anal plates of male subtriangular, with lobes or projections; tenth sternite with extensive wings, bearing prominent processes; aedeagus with two paired plates; parameres fused anteriorly. Anal plates of female small, rounded; ninth sternite divided, with a papiliform process on each plate.

Genotype: *Megalomus tortricoides* Rambur.

The life history of the Nearctic Megalomus is unknown. In the European species, according to Killington, the eggs have a sculptured chorion; the larva has a broader head than in Hemerobius, the third segment of the antennae is slender and hardly longer than the first, and the jaws are short and stout.

The venation in this genus is excessively variable. In most species the number of branches of the radial sector in the fore wing is greater than that in other genera; but in a few species the individual variation is so great that this difference cannot be regarded as generically rigid. Similarly, the point of furcation of MP in the hind wing, although furnishing diagnostic characteristics for other genera, is highly variable in Megalomus. The only venational feature which I have found sufficiently constant in Megalomus to be used in the generic key is the position of the basal cross-vein between R1 and Rs in the hind wing, with respect to the origin of R5 (or R4 + 5), and even this fails in some specimens.

Because of its instability the wing venation does not provide satisfactory specific characteristics and this is also true of the wing markings. The shape of the wing, however, is stable enough within the species for this purpose. The male genitalia, which incidentally are markedly different in Megalomus from those of other Hemerobiid genera except Boriomyia, furnish excellent specific characteristics in most cases.

The genus Megalomus has a wide distribution, occurring in Europe, Asia, northern Africa, South America, Central America and North America. It is a small genus, however, and only four species have been found in the Nearctic region. These may be distinguished by the following key:

1. Costal area of fore wing gradually broadened at base ....*minor* Banks (p. 242)
   Costal area of fore wing abruptly broadened at base 2
2. Fore wing broadly subtriangular; apex pointed and much nearer to the anterior margin than to the central line of the wing
   angulatus, n. sp. (p. 242)
   Fore wing broadly oval; apex rounded and about at the central line of the wing 3
3. Cross-veins between Cu1 in the fore wing in line with the outer gradates, the whole series forming a curved line parallel with the outer margin ....*moestus* Banks (p. 240)
   Cross-veins between the branches of Cu1 in the fore wing in line with the inner gradates, the whole series forming a straight line across the wing ....*uniformis* Banks (p. 241)

Megalomus moestus Banks

Figures 41, 42; plate 2, figure 17

Megalomus moestus Banks, 1895, Trans. Amer. Ent. Soc., 22: 314; Banks, 1905, ibid., **32:** 43.
Megalomus latus Banks, 1903, Proc. Ent. Soc. Wash., **5:** 240; 1905, ibid., **32:** 43.

Face varying from light to dark brown, sometimes reddish brown; glabrous; antennae greyish yellow; vertex, pronotum and mesothorax medium and dark brown, somewhat variegated; legs greyish-yellow; abdomen dark brown. Fore wing: length, 7–10 mm.; width, 3.8–5 mm.; broadly and nearly symmetrically oval; costal area very broad, as in all species of the genus, but not so abruptly widened basally as in *uniformis;* Rs with from 5–7 branches leading from R1 + Rs; inner gradate veins arranged in either a straight or broken line; outer gradate veins between the branches of Cu1 forming a continuous line with the outer gradates above; membrane either hyaline or slightly brownish; inner gradate veins strongly margined, forming an oblique streak across the wing, though its extent is variable; usually the membrane on the proximal side of the inner gradates is much darker than that on the distal side; outer gradates of radial sectors usually margined, but the degree of margination very variable; inner angle of wing and region of gradate veins in cubitus marked with dark brown; several irregular and faint, brown maculations are usually present over wing membrane in addition to the marginations of veins; costal area usually spotted with eight or more dark brown maculations. Anal plates of male typical of the genus; tenth sternite with flattened lateral "wings" and a narrow bridge; epimeres fully as long as phallus, strongly curved ventrally as seen in lateral view; phallobase with a small median protuberance posteriorly; plates of aedeagus elongate.

Holotype: Sante Fé, New Mexico, July (T. D. A. Cockerell); in the Museum of Comparative Zoology. Since this specimen has the abdomen missing, its sex is unknown.

Distribution: NEW MEXICO (Santa Fe, Hot Springs, Pecos, Bedah, Las Vegas); ARIZONA

(Biboquwari Mts., Huachuca Mts., Palmerlee, Globe, Chiricahua Mts.); CALIFORNIA (Claremont, Yosemite Valley); UTAH (Logan, Provo, Vineyard, Salt Lake City, Stockton, Eureka); COLORADO (Estes Park, Georgetown, Boulder, Colorado Springs, Golden, Manitou); TEXAS (El Paso Co.; Ft. Davis, 5000 ft., Jeff Davis Co.); WYOMING (Laramie). The adults have been collected from June through September.

This is the largest of our Megalomus. It is unusually variable in venation and in color markings on the wings, especially in the extent of the dark brown around the inner gradate veins. Banks' *latus* was based on three specimens, now in the United States National Museum; the holotype, from Williams, Arizona, is a female; one paratype, from Las Vegas Hot Springs, New Mexico, is a female (August 6) and the other, from the same locality (August 13) has the abdomen missing. *Latus* was separated from *moestus* on the extent of the wing markings around the gradate veins. From an examination of the numerous specimens of *moestus* which have passed through my hands, however, I am convinced that the differences indicated for the two species do not hold; there are all gradations in the extent of the markings, and the male genitalia are the same throughout, even in details.

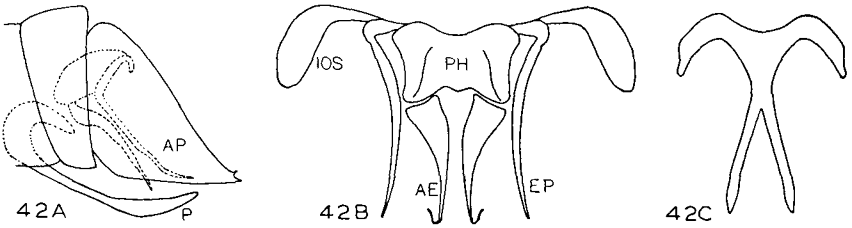


FIGURE 42. *Megalomus moestus* Banks. A, terminal abdominal segments of male; B, same, lateral view; C, parameres of same, dorsal view. PH, phallobase; EP, epimeres; other lettering as in figure 2.

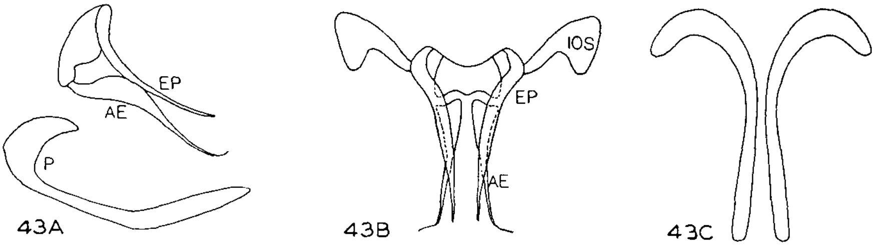


FIGURE 43. *Megalomus angulatus,* n. sp. A, tenth sternite and parameres of male (paratype), lateral view; B, tenth sternite of same, dorsal view; C, parameres of same, dorsal view. Lettering as in figure 42.

Megalomus uniformis Banks

Megalomus uniformis Banks, 1935, Psyche, **42:** 56.

Entire body, including antennae and legs, pale brown. Fore wing: length, 6 mm.; width, 3.2 mm.; membrane pale yellow, with only faint traces of light brown maculations; both series of gradate veins margined with light brown; costal area very broad, even more so than in *moestus* and more abruptly widened at base than in *moestus;* the wing as a whole is broader than that of *moestus* and is very nearly symmetrically oval; the apex is very broadly rounded; the gradate veins of the cubitus form a continuous line with the inner gradate veins, not with the outer series as in *moestus*. Hind wing: hyaline, without maculations. The male is unknown. The anal plates of the female are so very similar to those of *moestus* that I can detect no differences.

Holotype (♀): Brownsville, Texas; June (F. H. Snow); in the Museum of Comparative Zoology.

This species is known only by the holotype. It may be essentially a Mexican species which enters into the United States only in the region around Brownsville. We can base our conclusions only on the wing structure, but there seems little doubt that this species is distinct from *moestus*. Although the unusual arrangement of the cross-veins in the cubital region may be individual rather than specific, it is very improbable that the unique wing and body coloring, as well as the shape of the costal area, falls into this category.

Megalomus angulatus, n. sp.

Figure 43; plate 2, figure 18

Face light to medium brown, vertex a little darker; pronotum and mesonotum and abdomen medium to dark brown; legs pale yellow; first two antennal segments light brown, the rest dark brown. Fore wing: 6.5–7 mm.; width, 2.7–3 mm.; broadly subtriangular; apex pointed, much closer to anterior border than to mid-line of wing; costal area nearly as broad as in *moestus;* wing membrane hyaline or nearly so; maculations grey-brown; gradate veins margined with dark brown, forming two conspicuous oblique streaks across the wing; membrane with numerous small, greyish brown maculations, best developed distally, where they form an irregular reticulation and a faint streak from the very apex of the wing to the outer gradate series; cross-veins between the branches of Cu forming a part of the outer gradate series; apical and posterior borders of wing margined with dark brown; outer gradate veins between branches of Rs arranged in nearly a straight line, not curved as in *moestus.* Hind wing: hyaline, with the apex and posterior margin slightly grey-brown. Anal plates of male triangular; tenth sternite like that of *moestus,* but with smaller "wings"; plates of aedeagus slender; epimeres nearly straight in lateral view, not strongly curved as in *moestus;* parameres simple, as in *moestus,* but completely separated. The anal plates of the female are like those of *moestus.*

Holotype (♂): Ithaca, New York, September 3, 1939 (J. S. Franciemont); in the entomological collection of Cornell University. Allotype: Same locality data, August 3, 1939; in the same collection.

Paratypes: 1♂, Niagara Glen, Ontario, June 8, 1926 (G. S. Walley); in the Canadian National Collection, Ottawa.—1♀, Ithaca, New York, June 13, 1915; 1♀, Milford, New Hampshire, June 11; both in the Museum of Comparative Zoology.—1♂, Naples, Maine, August 20, 1934 (R. H. Beamer); in the University of Kansas Museum.

This striking species is close to *moestus* in general form, but differs in having a subtriangular fore wing, which is most unusual for a *Megalomus,* and also by the wing markings, which are not of the pattern ordinarily found in the genus. Differences are also evident in the male genitalia. The chief interest of the species lies in the fact that it is the first record of the genus east of the Rocky Mountain region.

In addition to the above mentioned individuals, I have seen four specimens apparently identical with the types in all respects: ♂, Pima Co., Arizona, July 29, 1927 (R. H. Beamer); ♀, Baboquivari, Arizona, July 19, 1934 (R. H. Beamer); and 2♀, near Sabinas Hidalgo, Nuevo Leon, Mexico, June 7, 1932 (Hobart Smith). Since these specimens were collected at places remote from the holotype locality, I have not designated them paratypes. The distribution indicated by these four specimens and the types is a most unusual one, but I have been utterly unable to discern any differences between the eastern and western lots. It may be that the species will eventually turn up in the Rocky Mountain region, in which case the distribution would not be unlike that of many other insects.

Megalomus minor Banks

Figure 44

Megalomus minor Banks, 1905, Invert. Pacifica, **1:** 90; 1905, Trans. Amer. Ent. Soc., **32:** 43.[14]

Head, antennae, legs yellow; vertex with a thin and rather indistinct median dark stripe; thorax and abdomen dark brown. Fore wing: length, 5 mm.; width, 2.5 mm.; costal area broad, but only gradually widened at the base, not abruptly, as in the other species of the genus; wing membrane hyaline, slightly yellowish; light brown maculations around the inner and outer gradate veins; a patch of dark brown near the outer gradate veins of the cubitus; Rs in the type with only four branches arising from the stem R1 + Rs. Anal plates of male as in *moestus;* tenth sternite with broader wings than in the latter; epimeres as long as the aedeagus; plates of aedeagus apparently firmly attached to phallobase; parameres very complex, as seen in dorsal view, with an anterior, triangular basal piece, and two posterior arms, with an oblique tooth-like projection between the base and the arms.

Types: Three cotypes were mentioned by Banks, two from San Marcos, Nicaragua, and one from Ormsby Co., Nevada (G. F. Baker). The latter specimen, a male, is in the Museum of Comparative Zoology and is here designated the lectotype. One of the Nicaragua specimens, a female, is also in the Museum of Comparative Zoology, but I have not been able to find the second specimen from that locality. Although the occurrence of this species in Nicaragua and Nevada seems rather unlikely, I have been unable to discover any differences in the specimens at hand. The examination of a male from San Marcos will definitely settle the question.

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[14] This species was described as new in both of the papers listed, but the Invertebrata Pacifica was actually published first.

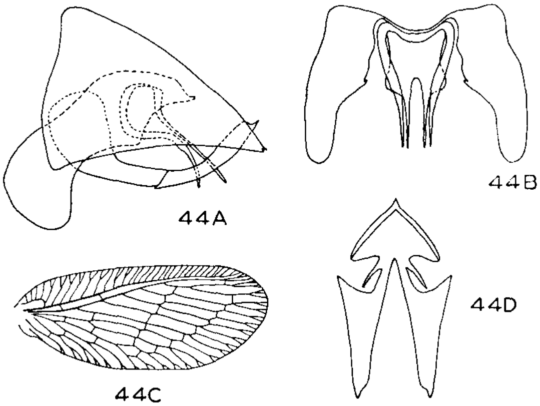

FIGURE 44. *Megalomus minor* Banks. A, terminal abdominal segments of male (holotype), lateral view, B, tenth sternite of same, dorsal view; C, fore wing; D, parameres, dorsal view. Lettering as in figure 42.

This species is unusual for a Megalomus in many respects. The wing venation, as pointed out by Banks, is more open than is normal in the genus. The parameres, moreover, are not at all like those of *moestus* or *angulatus,* but instead are very similar to those in Boriomyia. On the other hand, there are several characteristics of *minor* which are perfectly typical of Megalomus, such as the form of the tenth sternite and the three main forks of Rs in the hind wing, as well as the position of the radial cross-vein in the hind wing with respect to the origin of R5. These several points of similarity with the species of Megalomus more than balance the difference in the form of the parameres.

Genus *Boriomyia* Banks

Boriomyia Banks, 1904, Proc. Ent. Soc. Wash., **6:** 209 (*nec* Banks, 1905); Killington, 1937, Monogr. Brit. Neuropt., **2:** 256.

Allotomyia Banks, 1930, Psyche, **37:** 224.[15]

Fore wing: broadly oval; costal area very broad; recurrent humeral vein present; costal veins forked; three or four branches of Rs arising from stem R1 + Rs (not including MA); basal piece of MA absent or at very base of wing; two series of gradate veins; more than eight veins in outer series; Cu1 forked only once between m-cu and outer gradate series.

Hind wing: Rs having slight contact with MA; Rs diverging slightly towards R1 after its origin and connected to it by a short basal cross-vein, which is far basal to the origin of R4 + 5; Rs with two main forks; basal piece of MA usually sigmoidal; furcation of MP either at level of separation of Rs from MA or slightly distal to it; two series of gradate veins, more than four in the outer series.

Anal plates slenderly triangular, without projections or distal processes; tenth sternite with extensive wings bearing long processes arising distally and extending ventrally; aedeagus with paired plates; parameres fused anteriorly, with excised outer margins. Anal plates of female small, rounded; ninth sternite small, divided, concealed within eighth; each plate of ninth sternite bearing a raised, semi-spheroid area, with radiating spines, similar to the papiliform processes in Megalomus, but not quite so large.

Genotype: *Hemerobius fidelis* Banks.

The immature stages of the species of this genus are entirely unknown.

The affinities of this genus have been uncertain in the past and I believe they have been misunderstood. The genotype species, together with *speciosa,* was for a time placed by Banks in the same genus as *disjuncta* and its relatives. Killington also apparently regarded it as closely allied to Kimminsia. However, a study of the male and female genitalia of *fidelis* and *speciosa* shows that these insects are really very closely related to Megalomus, not to Kimminsia or Hemerobius. The anal plates and the tenth sternite are surprisingly similar in Megalomus and Boriomyia, the chief difference in the male genitalia being in the form of the parameres. In this connection the genital structure of *Megalomus minor* Banks is particularly interesting, since the parameres of that species are more like those of *fidelis* and *speciosa* than they are of other Megalomus. The ninth sternite of the female abdomen in Boriomyia is divided like that in Megalomus, and likewise possesses the semi-spheroid area with radiating spines, characteristics which do not occur, so far as I am aware, in any other Hemerobiid genera. Furthermore, it is difficult to find venational differences between the genera which hold for all species of each. It has been thought in the past that Megalomus could be distinguished from Boriomyia and other genera by the greater number of branches of the radial sector; but an examination of a large series of specimens of Megalomus shows that a four-branched radial sector occurs commonly in some species of the genus. In view of the fact that this type of radial sector is also found in Boriomyia (as well as in some other genera of Hemerobiidae) the number of branches of Rs can hardly serve as a reliable characteristic of Megalomus. The only venational differences between Megalomus and Boriomyia which I have found to hold almost without exception is the position of the basal radial cross-vein in the hind wing. In Megalomus this cross-vein is very nearly at the point of origin of R5 (or R4 + 5) or even distal to it; in Boriomyia the cross-vein is far removed (proximal) from the origin of R4 + 5 (or R5). It is probable, however, that additional species of Boriomyia, especially from other regions, will show that this characteristic is variable in the genus to such an extent that it cannot be used as a generic distinction. If that does turn out to be the case, it will presumably be necessary to synonymize Boriomyia with Megalomus.

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[15] See page **215**.

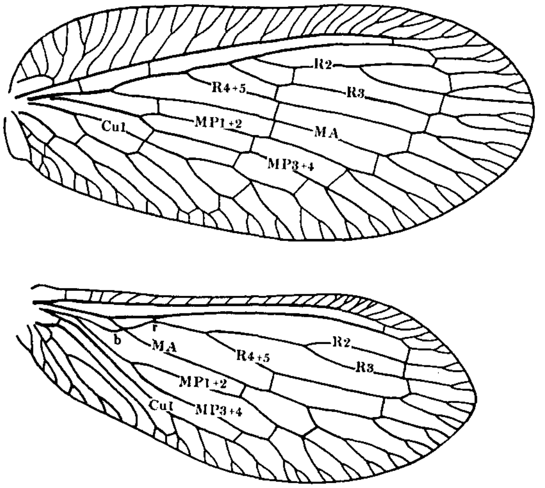

FIGURE 45. Wing venation of *Boriomyia fidelis* (Banks). Lettering as in figure 1.

The genus Boriomyia is at present known only from the Nearctic region, where it is represented by the two following species:[16]

Fore wing with two transverse brown bands, one along the inner gradates, the other along the outer .... *fidelis* Banks (p. 244)

Fore wing with very conspicuous dark brown spots around the distal cross-veins of Cu1, the inner and outer gradates and a few other cross-veins *speciosa* Banks (p. 245)

Boriomyia fidelis (Banks)

Figures 45, 46

Hemerobius fidelis Banks, 1897, Trans. Amer. Ent. Soc., **24:** 27.

Boriomyia fidelis Banks, 1904, Proc. Ent. Soc. Wash., **6:** 209; 1905, Trans. Amer. Ent. Soc., **32:** 36.

Allotomyia fidelis Banks, 1930, Psyche, **37:** 224.

Face yellow to brown, in northern specimens very dark brown just below antennae; antennae pale yellow to dark brown, almost black in northern specimens; pronotum and mesonotum medium brown to dark brown; metanotum and abdomen dark brown; legs pale yellow. Fore wing: length (average), 4–7 mm.; width, 1.8–3.2 mm.; membrane hyaline; markings light brown (dark brown in northern specimens) forming two transverse bands, one in the region of the inner gradates and the other in the region of the outer gradates of Rs only; in the more heavily marked specimens there is a large area of brown in the region of the gradate cross-veins of the cubitus; a heavy spot of dark brown at m-cu cross-vein. Hind wing: membrane hyaline, but anterior third of wing proximal of pterostigma is smoky. Anal plates of male elongate; tenth sternite with broad "wings" and a pair of prominent acute processes extending posteriorly; aedeagus with plates coalesced basally, forming a pair of divergent broad arms; parameres large, with a broad median plate, and two lateral plates, the latter having a prominent tooth near the middle.

Holotype (♀): Gowanda, New York, June 25 (E. P. Van Duzee); in the Museum of Comparative Zoology. Allotype, by present designation: Raleigh, North Carolina, May 24, 1932 (C. S. Brimley).

Distribution: NORTH CAROLINA (Raleigh, Tryon, Benson, Rock Point); SOUTH CAROLINA (Tigerville); VIRGINIA (Fairfax Co.); MARYLAND (Plummer's Island; Beltsville); WEST VIRGINIA (White Sulpher Springs, Greenbier Co.); PENNSYLVANIA (Jeanette, Pittsburgh, Natrona); DISTRICT OF COLUMBIA (Washington); NEW JERSEY (Lakehurst); MASSA-

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[16] *Boriomyia* (*Allotomyia*) *borealis* Banks is a synonym of *Wesmaelius longifrons* (Walker).

CHUSETTS (Lexington); NEW HAMPSHIRE (Franconia; White Mts.); ONTARIO (Bobcaygeon, July 10, J. McDunnough); BRITISH COLUMBIA (Rolla, July 21, 1927, P. N. Vroon); TEXAS (Terlingua, May 3, 1925); MISSISSIPPI (Shuqualak); ILLINOIS (Elizabethtown, May; Thebes, July). The adults have been collected from May through September. The records are widely scattered, but they indicate that *fidelis* occurs throughout the eastern United States and Canada, from latitude 35° to 45°, and west to longitude 83°. The occurrence of the species in British Columbia is most surprising; I have seen only the one specimen (from Rolla), but that is a male and exhibits no differences in structure of any nature from the eastern specimens.

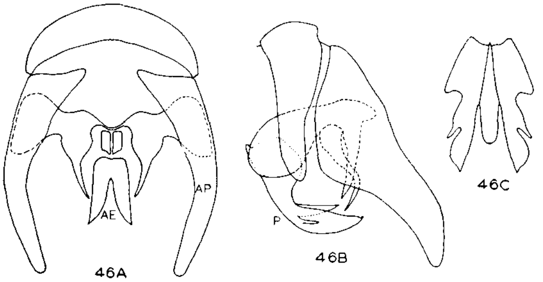


FIGURE 46. *Boriomyia fidelis* (Banks). A, terminal abdominal segments of male (allotype), dorsal view; B, same, lateral view; C, parameres of same, dorsal view. Lettering as in figure 42.

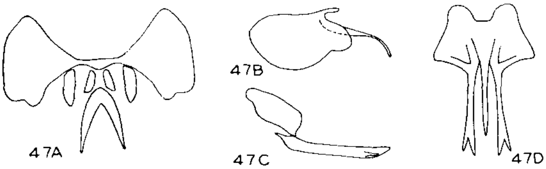


FIGURE 47. *Boriomyia speciosa* (Banks). A, tenth sternite of male (allotype), dorsal view; B, same, lateral view; C, parameres of same, lateral view; D, same, dorsal view.

The female holotype of *fidelis* is unlike all the other specimens which I have seen in possessing a cross-vein between the lower branch of Rs and R1; I can interpret the presence of this cross-vein in the type only as an abnormality.

Fidelis is readily distingushed from the other two species of the genus; from *minor* by the abruptly broadened costal margin, and from *speciosa* by the presence of the two wide transverse bands on the fore wing.

Boriomyia speciosa (Banks)

Figure 47

Hemerobius speciosus Banks, 1904, Can. Ent., **36:** 62.

Boriomyia speciosa Banks, 1904, Proc. Ent. Soc. Wash., **6:** 209; 1905, Trans. Amer. Ent. Soc., **32:** 37.

Allotomyia speciosa Banks, 1930, Psyche, **37:** 224.

Head medium to dark brown; thorax and abdomen very dark brown; antennae and legs yellow. Fore wing: length, 7 mm.; width, 3 mm.; costal area broad, as in *fidelis;* membrane hyaline; markings very dark brown, consisting of spots along the radius at the origin of the several branches of Rs, along the inner gradate veins, along the apex, and at the cross-veins of Cu1. Hind wing: as in *fidelis,* with apex and part of anterior border brown. Anal plates as in *fidelis;* tenth sternite with wider and shorter posterior processes than in *fidelis;* plates of aedeagus slender; parameres very different from those of *fidelis,* having a long, slender, median process extending posteriorly, and a pair of slender, lateral processes forked distally.

Holotype (♀): Plummer's Island, Maryland, September 9; in the Museum of Comparative Zoology. Allotype, by present designation: Falls Church, Virginia, August 2 (N. Banks); in the Museum of Comparative Zoology.

In addition to the types, I have seen only three other specimens: a female from near Plummer's Island, September 15 (W. L. McAtee), and two from Sanibel Is., Florida, May 13, 1916.

Speciosa resembles *fidelis* in general habitus, but it is readily distinguished from it by the dark spots on the fore wings, in contrast to the lighter, transverse bands in *fidelis*. The male genitalia are in general similar to those of *fidelis,* but the parameres have a very different shape. The terminal abdominal segments of the females of the two species are apparently identical.

Genus *Micromus* Rambur

Micromus Rambur, 1842, Hist. Nat. Ins. Neuropt. 416; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 44; Killington, 1936, Monogr. Brit. Neuropt., **1:** 250.

Eumicromus Nakahara, 1915, Annot. Zool., **9:** 36; Killington, 1936, Monogr. Brit. Neuropt., **1:** 257.

Stenomicromus Kruger, 1922, Stett. Ent. Zeit., **83:** 171.

Pseudomicromus Kruger, 1922, ibid.: 172.

Paramicromus Kruger, 1922, ibid.: 172.

Fore wing: broadly or slenderly oval; costal area narrow at base; recurrent humeral vein present; costal veinlets forked; three or more branches of Rs arising from stem R1 + Rs (not including MA); basal piece of MA absent; cross-vein between MA and MP1 + 2 shortly after origin of the latter; two series of gradate veins, five cross-veins or more in the outer series.

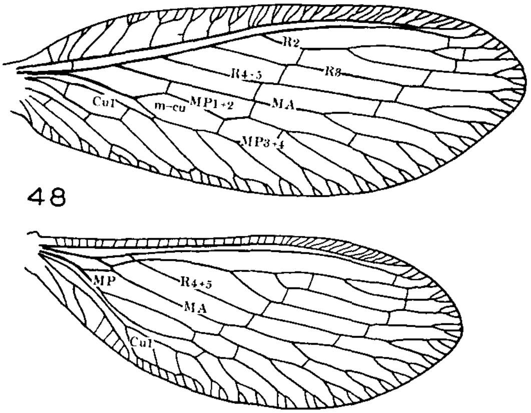
Hind wing: Rs usually connected to MA by a cross-vein or (rarely) in actual contact with MA; Rs connected to R1 by a cross-vein usually after the separation of MA from Rs (or the connecting cross-vein); furcation of MP at about the level of separation of MA from Rs (or the connecting cross-vein); basal piece of MA usually very conspicuous; two series of gradate veins, five or more in the outer series.

Anal plates of male suboval, with a posterior process arising from the lower margin; aedeagus with two plates, somewhat divergent; parameres fused proximally. Anal plates of female rounded; eighth sternite without sclerotized plates.

Genotype: *Hemerobius variegatus* Fabricius.

The egg has a smooth chorion, except for some pitting anteriorly. The larva is like that of Hemerobius, but has more slender jaws. The life history of three Nearctic species is known: *posticus* Walker (Smith, 1923); *subanticus* Walker (Smith, 1934);[17] and *angulatus* Stephens (Aubrook, 1935).

Several attempts have been made to divide this genus. Eumicromus (genotype *M. numerosus* Navas, Asia) was established by Nakahara (1915) for certain species previously included in Micromus. Although Killington has accepted this genus in his monograph, the proposed distinctions between Micromus and Eumicromus do not hold satisfactorily for the Nearctic species. Eumicromus was originally separated from Micromus by Nakahara on two differences: in Eumicromus Rs of the fore wing has from 4 to 8 branches and M and Cu of the hind wing are partially coalesced; in Micromus Rs of the fore wing has 3 or 4 branches and M and Cu of the hind wing are free. It is significant to note that the number of branches of Rs in the fore wing overlaps in the two genera, four being common to certain species of both. On the basis of the structure of M and Cu in the hind wing, which seems to be fairly constant in all species, all of the Nearctic species formerly in Micromus belong to Eumicromus, although certain of these are closer in other respects to *variegatus*, the genotype of Micromus, than to the other species. Killington indicated no additional differences between the two genera except the shape of the wings, those of Micromus being narrow and elongate, and those of Eumicromus being broadly oval. However, two Nearctic species, *subanticus* and *variolosus*, although belonging to Eumicromus on the basis of the structure of M and Cu in the hind wing, have the narrow and elongate wings as in *variegatus*. It is my conviction, therefore, especially since no unusual genital differences exist between the two groups, that Eumicromus is not a valid genus.



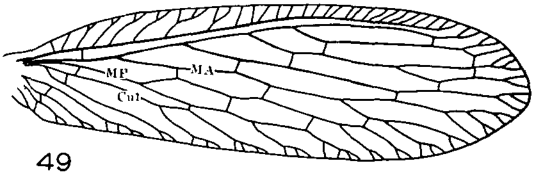


FIGURE 48. Wing venation of *Micromus posticus* (Walker). Lettering as in figure 1.

FIGURE 49. Venation of fore wing of *Micromus variolosus* Hagen. Lettering as in figure 1.

The Nearctic species of Micromus may be readily recognized on wing characteristics, such as the arrangement of the inner gradate veins of the fore wing and the point of furcation of Cu1a in the fore wing. The number of branches of Rs, which has previously been used as a difference between *montanus* and the other Nearctic species, does not hold in a sufficiently high percentage of specimens to be useful taxonomically. The male genitalia show very good specific differences, most of them being discernible without dissection. The terminal ab-

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[17] Smith determined the species as *variolosus*, which does not, however, occur in Kansas (at least in the eastern part of the state), where the insects were obtained.

dominal segments of the female are very much alike in all species.

Micromus has a wide and nearly cosmopolitan distribution. The five Nearctic species have an extensive range within the region, some being mainly northern and others mostly southern. One species, *angulatus* Stephens, is holarctic. The Nearctic species may be distinguished as follows:

Key to the Nearctic Species of Micromus

1. Inner gradate veins of fore wing much more than their lengths apart 2
Inner gradate veins at most only their lengths apart 3
2. Thorax and vertex of head very dark brown; wing markings dark brown, almost black *variolosus* Hagen (p. 251)
Thorax and vertex of head medium brown or light brown; wing markings light brown *subanticus* Walker (p. 250)
3. Inner gradate vein of fore wing between MA and MP1 + 2 basal to the one above it, the gradates forming a regular series *angulatus* Stephens (p. 247)
Inner gradate vein of fore wing between MA and MP1 + 2 distal to the one above it, the gradate series being irregular at this point 4
4. Cu1a of fore wing forked deeply, at least to half the distance from the hind margin to the cross-vein joining it to MP3 + 4 or to the point of coalescence of M3 + 4 and Cu1a *montanus* Hagen (p. 249)
Cu1a forked or twigged very nearly at the wing margin ....*posticus* Walker (p. 248)

Micromus angulatus (Stephens)

Figure 50; plate 2, figure 19

Hemerobius angulatus Stephens, 1836, Illus. Brit. Ent., Mand., **6:** 106.[18]

Micromus angulatus Hagen, 1889, Proc. Bost. Soc. Nat. Hist., **23:** 280; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 45.

Micromus jonas Needham, 1905, Bull. N. Y. State Mus., **86:** 15.

Face uniformly light brown; antennae pale brown; vertex brown, with some rugose sculpturing on posterior half; pronotum nearly uniformly brown, there being some dark brown laterally; mesonotum uniformly brown; abdomen dark brown. Fore wing: length (average), 7 mm.; width, 3 mm.; broadly oval, apex rounded; membrane yellow-brown to light brown; veins and maculations brown; maculations forming an irregular network; gradate veins margined; general effect of markings on wings is three obliquely transverse stripes and one or two short longitudinal ones distally; Rs with from 4 to 6 branches; the inner gradate veins form a straight line, the one between MA and MP1 + 2 being in line (slightly basal) with the one above it; points of contact of inner gradate veins with the longitudinal veins close together. Hind wing: MP3 + 4 not coalesced with Cu1; membrane hyaline. Anal plates of male more or less rounded as seen from the side, with a pair of straight, long posterior processes arising from the ventral surface; tenth sternite large, with two prominent, flattened anterior lobes; plates of aedeagus divergent, slightly curved distally; parameres coalesced anteriorly, forming a pair of curved, contiguous arms posteriorly.

Holotype (♀): in the British Museum; no collecting data are known, but the specimen was probably taken near London.

Distribution: QUEBEC (September–October); ONTARIO (May, July–October); MAINE (Machias, August 10); VERMONT (Woodstock, August 11); NEW HAMPSHIRE (White Mts.); NEW YORK (Fulton Co.; Cranberry Lake; Ithaca; Old Forge; Hillside, September 22); MICHIGAN (Chebaygan Co., July 27); WISCONSIN (Wittemberg, August 27; Brule, August 19); MINNESOTA (Twin Harbors, May, July–August); COLORADO (Selkirk Mts.); SOUTH DAKOTA (Custer Co.); MANITOBA (Stony Mts., October 8, 1911; Swan River, August 2); SASKATCHEWAN (Saskatoon, September 13); ALBERTA (Calgary); BRITISH COLUMBIA (Vernon, September 29; Point Grey, October 30; Agassiz, July 29); YUKON (Dawson, August 29). The species also occurs in Europe, from Finland and Siberia to Spain and Palestine (according to Killington). The most southern record known to me in the Nearctic region is in Colorado, and although no additional locality data are available for that specimen, it was probably taken at a high altitude.

The wings of this species are distinctly marked and have obvious venational peculiarities, such as the arrangement of the gradate veins. The genitalia are closest to those of *posticus*, but there are many obvious differences, such as in the shape of the aedeagus, as shown in the figures.

M. jonas Needham, based upon wings found in the stomach of a bullfrog, is unquestionably a synonym of *angulatus*. The author gives no definite characteristics for separating the two species, but merely states that the wings alone will distinguish it. His figures of the wings, however, reveal no differences of a specific nature. The radial sector of the fore wing illustrated has only three branches, instead of four, as is usually the case; but I have seen several specimens of *angulatus* with three branches in one wing and four branches in the opposite wing.

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[18] The European synonymy is not included here, since it has been listed in Killington's recent monograph of the British Neuroptera (1936).

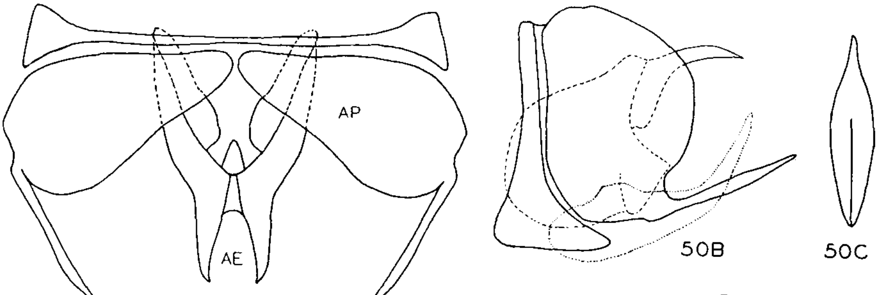

FIGURE 50. *Micromus angulatus* Steph. A, terminal abdominal segments of male, dorsal view; B, same, lateral view; C, parameres of same, dorsal view. Lettering as in figure 2.

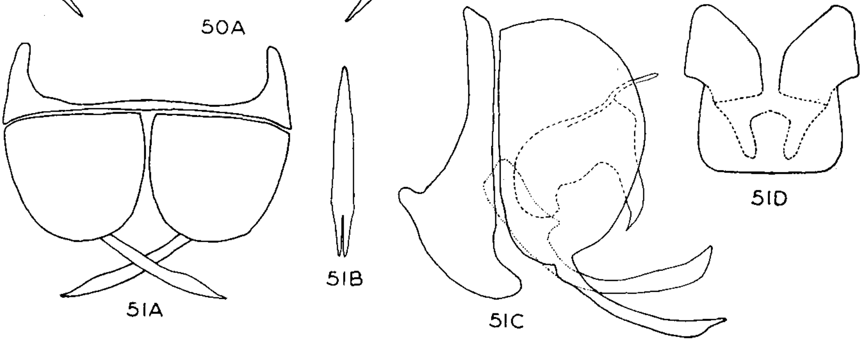

FIGURE 51. *Micromus posticus* (Walker). A, terminal abdominal segments of male, dorsal view; B, parameres of same, dorsal view; C, terminal segments of male, lateral view; D, tenth sternite of same, dorsal view.

Micromus posticus (Walker)

Figure 51

Hemerobius posticus Walker, 1853, List. Spec. Neuropt. Ins. Brit. Mus.: 283.

Micromus posticus Banks, 1905, Trans. Amer. Ent. Soc., **32**: 45.

Micromus insipidus Hagen, 1861, Syn. Neuropt. N. A.: 199; Hagen, 1886, Proc. Bost. Soc. Nat. Hist., **23**: 285.

Micromus sobrius Hagen, 1861, ibid.: 199.

Head, thorax and abdomen nearly uniformly brown, with some irregular darker areas on thorax; antennae and legs lighter brown. Fore wing: length, 9 mm.; width, 4 mm.; apex slightly pointed; wing membrane hyaline, but nearly covered with faint, greyish brown, irregular maculations; gradate veins lightly margined with brown, forming two very thin oblique transverse stripes; usually three or four branches of Rs; Cu1a with a very shallow distal fork or twigged at the margin; inner gradate vein between MA and MP1 + 2 distal to the one above, the gradate series being broken at this point; inner gradate veins less than their lengths apart. Hind wing: MP3 + 4 not coalesced with Cu1; membrane hyaline, no maculations. Anal plates of male short, almost semi-circular, with a long posterior process arising from the ventral margin; tenth sternite small, "wings" without lateral posterior extensions; aedeagus short, slightly curved, directed ventrally; a very wide median distal process of the tenth sternite extends above the aedeagus; parameres coalesced for nearly their whole length.

Types: Two cotypes (♂, ♀), from Georgia (Abbot); in the British Museum.

Distribution: This species is common over the eastern United States from Massachusetts westward to Minnesota and southward to Florida and Texas; in Canada the species has been found only in Ontario (Niagara, Norfolk, Vineland). I have seen no specimens from northern New England or the eastern Canadian provinces. A few specimens have been collected in Nebraska (Lincoln, Omaha), Kansas (Montgomery Co.; Riley Co.; Troy; Douglas Co.); Colorado (Pingree Park); North Dakota (Linton), and Arizona (Maricopa Co.).

Posticus is the commonest species of the genus in the Nearctic region. It is readily distinguished from *montanus* by the nature of the branching of Cu1, and in general appearance it does not even resemble the other species.

The types of *insipidus* Hagen and *sobrius* Hagen are in the Museum of Comparative Zoology; they are unquestionably *posticus,* as was suggested by McLachlan and as they have been subsequently regarded.

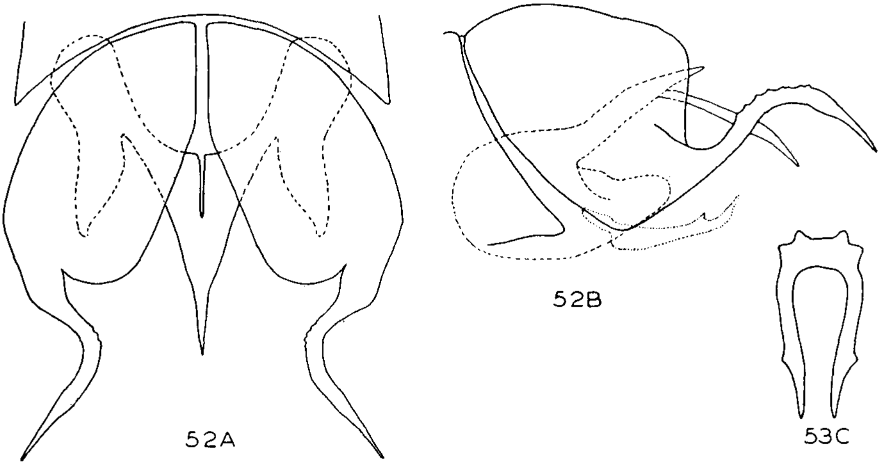

FIGURE 52. *Micromus montanus* Hagen. A, terminal abdominal segments of male (lectotype), dorsal view; B, same, lateral view; C, parameres of same, dorsal view.

Micromus montanus Hagen

Figure 52; plate 2, figure 20

Micromus montanus Hagen, 1886, Proc. Bost. Soc. Nat. Hist., **23:** 279; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 45.

Head uniformly light brown; pronotum and mesonotum also light brown, occasionally with a few variable darker areas; antennae and legs light brown; abdomen usually somewhat darker than the rest of the body. Fore wing: length (average), 7–11 mm.; width, 3–5 mm.; broad, slightly pointed; membrane hyaline; veins as a whole light brown and very faint, except where maculations occur; maculations yellow-brown; inner and outer gradate veins dark brown, as also are certain distal branches of Rs; markings consisting of the two thin gradate stripes and three short and broader distal bands between the outer gradates and the hind margin; five bands of Rs usually present, but specimens with four branches are not rare; inner gradate vein between MA and MP1 + 2 slightly proximal to the one above it, there being a break in the gradate series at this point; first fork of Cu1 much closer to the gradate vein between Cu1 and Cu2 than to the m-cu cross-vein; Cu1a forked more than half way from the wing margin to m-cu. Hind wing: hyaline, no maculations; MP3 + 4 not coalesced with Cu1. Anal plates of male with a very long and strongly arched posterior process, the dorsal surface of the arch being somewhat denticulate; tenth sternite also large, the "wings" giving rise to a pair of prominent posterior lobes; aedeagus long and rather slender; tenth sternite with a short median distal process over the aedeagus; parameres coalesced anteriorly, then divergent, forming a pair of long, pointed and slightly curved arms, with a prominent dorsal subapical tooth.

Types: The following cotypes were mentioned in the original description: 1♂, 3♀, White Mts., New Hampshire, July (Morrison); in the Museum of Comparative Zoology; 1♀, same, in the Canadian National collection; 1♂, Natick, Massachusetts, in the Museum of Comparative Zoology. The latter is designated the lectotype.

Distribution: QUEBEC; NOVA SCOTIA; MAINE; NEW HAMPSHIRE; MASSACHUSETTS; NEW YORK (Fulton Co., Greene Co.); CONNECTICUT (Salisbury); TENNESSEE

(Newfound Gap, Smoky Mts., 5000 ft., August 20); NORTH DAKOTA (Metagoshe); UTAH (Provo, Logan); COLORADO (Golden; Veta Pass; Rocky Mt. Nat'l. Park; Summit Co.); NEVADA (Ormsby Co., July 6); CALIFORNIA (Gold Lake Camp, Plumas Co., July 20, H. G. Dyar); ARIZONA (Graham Mt., July 26, 1933); BRITISH COLUMBIA (Ainsworth; Kokanee Mt.; Brookville; Kaslo; Hedley; Clinton; Hope Mts.); ALBERTA (Nordegg; Waterton Lakes; Banff; Lake Louise); IDAHO (Wallace); WASHINGTON (Northbend, King Co., July 7, 1920, E. C. Van Dyke). Most of the specimens have been collected during June, July and August, but a few were taken in May and September. Although the above records are somewhat spotty, the species apparently ranges across Canada and the northern United States, entering the south only at high altitudes. It seems to be absent from the plains region of United States and Canada.

Montanus is the largest species of our Micromus. As Hagen pointed out, it is close to the European *paganus* Linn., both having the venational peculiarities mentioned above; the genitalia, however, though of the same general form, differ in various details, as Hagen himself noted. The relationship between these two species is apparently analogous to that between *Hemerobius marginatus* Steph. (European) and *H. costalis* Carp. (Nearctic). From the other Nearctic species of its genus *montanus* is distinguished by the wing markings and especially by the nature of the forking of Cu1.

Micromus subanticus (Walker)

Figure 53; plate 2, figure 22

Hemerobius subanticus Walker, 1853, List. Spec. Neuropt. Ins. Brit. Mus.: 282.

Micromus subanticus Banks, 1905, Trans. Amer. Ent. Soc., **32:** 46.

Micromus angustus Hagen, 1886, Proc. Bost. Soc. Nat. Hist., **23:** 287; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 50.

Micromus nesoticus Navas, 1914, Bull. Brook. Ent. Soc., **9:** 16, fig. 3.

Head, including vertex, nearly uniformly light or medium brown; thoracic nota medium brown; abdomen dark brown; antennae and legs light brown. Fore wing: length, 7 mm.; width, 2.3 mm.; about three times as long as wide; membrane very light brown, nearly hyaline; veins brownish; Rs usually with three branches; MA and the outer gradates usually dark brown, forming a very thin longitudinal line, bent upwards distally; maculations grey, very faint and confined to the area around the gradate veins and some of the other cross-veins; inner gradate veins very widely separated, more than their length apart; Cu1a usually free from MP, but occasionally coalesced with it for a short distance. Hind wing: hyaline, no maculations; MP not fused with Cu1. Anal plates of male short, terminating in a pair of prominent posterior processes arising from the ventral border; tenth sternite large, the "wings" extended anteriorly and much broadened; plates of aedeagus divergent as seen from the side; parameres fused anteriorly for half their length, separating posteriorly to form a pair of short curved arms.

Holotype (♂): St. John's Bluff, East Florida; in the British Museum. Allotype, by present designation: Winter Park, Florida, January 24 (E. M. Davis); in the Museum of Comparative Zoology.

Distribution: In the southern part of the United States, below latitude 37°, *subanticus* has been found commonly across the continent from Florida to California; north of this latitude it occurs in the eastern half of the country only, i.e. east of about longitude 97°, where it extends as far north as Massachusetts (lat. 43°). I have seen no specimens from any part of Canada. In the Gulf States and California the adults have been collected during all months of the year; further north they have been taken from June to October.

This species and the following (*variolosus*) differ from our other species of Micromus in having slender wings and widely separated inner gradates. *Subanticus* and *variolosus* are very similar to each other, however. There seem to be no constant venational characteristics which serve to distinguish them readily, but this can be done by the body color and wing markings. *Variolosus* is much the darker species, both in body and wing coloring. The male genitalia also show good specific differences, as indicated in the figures.

Hagen's *angustus* was based upon seven specimens of this species from Florida and North Carolina; six types are in the Museum of Comparative Zoology and one is in the Canadian National collection. Hagen himself stated after his description that *angustus* was perhaps *subanticus,* but he separated the two on the number of branches of the radial sector. The branching of the radial sector in Micromus, however, is very variable, and furnishes no specific differences.

Navas' *nesoticus* is also this species. This was based upon an individual from Yaphank, Long Island, New York, and was supposed to differ from *subanticus* by having only "three radial sectors, in place of four." Such venational differences, as already mentioned, are of individual occurrence in Micromus.

Micromus variolosus Hagen

Figure 54; plate 2, figure 21

Micromus variolosus Hagen, 1886, Proc. Bost. Soc. Nat. Hist., **23:** 284; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 46.

Head with face light brown, rarely dark brown in center; vertex, thorax and abdomen very dark brown, almost black. Fore wing: length (average), 7 mm.; width, 2.2 mm.; shape as in *subanticus;* membrane hyaline; markings brown, much darker than in *subanticus;* veins dark brown, mostly interrupted; maculations most prominent along the posterior border and distal third of the wing; outer gradate veins heavily margined, forming a short but distinct oblique streak which is easily visible; inner gradate veins widely separated, as in *subanticus;* Rs usually with three branches. Hind wing: membrane hyaline, no maculations; MP2 + 3 not fused with Cu1. Anal plates of male short, with long posterior ventral process; tenth sternite large, the "wings" giving rise to a pair of long posterior extensions; plates of aedeagus parallel in dorsal view, almost straight from the side; a short distal process present over the aedeagus; parameres coalesced for less than half their length, forming two strongly curved posterior arms.

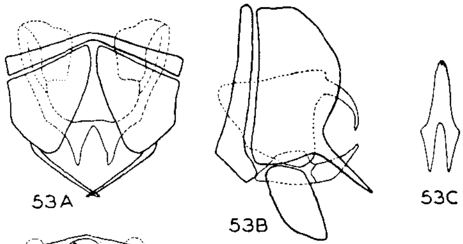

FIGURE 53. *Micromus subanticus* (Walker). A, terminal abdominal segments of male, dorsal view; B, same, lateral view; C, parameres of same.

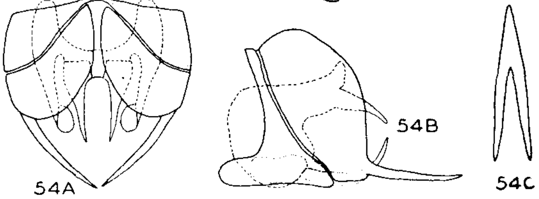

FIGURE 54. *Micromus variolosus* Hagen. A, terminal abdominal segments of male (allotype), dorsal view; B, same, lateral view; C, parameres of same, dorsal view.

Holotype (♀): Denver, Colorado; in the Museum of Comparative Zoology. Allotype, by present designation: Rainbow Natural Bridge, Utah, July 5 (C. T. Brues); in the Museum of Comparative Zoology.

Distribution: BRITISH COLUMBIA (Hedley, Lilloeet); WASHINGTON (Pullman, Toppenish); IDAHO (Hubbs Butte); OREGON (Biggs; Pendleton; Klamath Co., 6000 ft.); WYOMING (near Lusk); UTAH (Provo, Logan, Eureka, Weber Canyon, Tooele, Rainbow, Heber, St. George, Bryce Canyon); NEVADA (Reno; Humbolt; Dixie Nat. Forest); CALIFORNIA (Oroville, Colton, Needles, Indio, San Jacinto Mts. San Gabriel Mts., Riverside, Inyo Co.); NEW MEXICO (Pecos, Las Cruces, Mesa Verda, Otero Co., Torrance Co.); ARIZONA (Williams, Flagstaff, Washington Mts., Nogales, Tucson, Chircahua Mts., Santa Rita Mts., Prescott, Congress Junction); COLORADO (Mt. Manitou, Salida, Maybel, Tabernash, Florissant, Boulder, Denver, Saguache, Platte Canyon, Colorado Springs). Most of the specimens have been collected from May through August, but in California adults have been found during March and December. It is interesting that in spite of the close resemblance of *variolosus* and *subanticus*, the two species have very different ranges, and that only in three states (California, Arizona, and New Mexico), so far as our present records are concerned, do the ranges of the two species coincide.

As noted in the key, this species is readily separated from the former by the much darker wing and body coloration.

Genus *Psectra* Hagen

Psectra Hagen, 1866, Stett. Ent. Zeit., **27:** 376; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 44; Killington, 1936, Monogr. Brit. Neuropt., **1:** 245.

Fore wing: elongate oval; costal area broadened above furcation of MP, but not abruptly narrowed basally, as in Micromus; recurrent humeral vein absent; few costal veinlets forked; Rs with two branches, R2 + 3 arising near the apex of wing, R4 + 5 coalesced proximally with MA; basal piece of MA present, remote from base; one series of gradate veins. Hind wing: either fully formed or vestigial. When fully developed, the hind wing is similar in size and shape to the fore wing; MA coalesced with Rs for a considerable distance; no gradate series. Anal plates of male small; ninth tergite narrow, with the lower margin prolonged into a curved tooth posteriorly; apparently no plates of the aedeagus are present; parameres fused. Anal plates of female small; ninth sternite large, rounded; eighth sternite without a sclerotized plate.

Genotype: *Hemerobius dipterus* Burmeister.

This aberrant genus contains only the genotype species. Its affinities are very uncertain, though it is doubtless closely related to Nyrma Navas, from Asia Minor. Its life history is entirely unknown.

Psectra diptera (Burmeister)

Figure 55; plate 3, figure 23

Hemerobius dipterus Burmeister, 1839, Handb. der Ent., **2:** 973.

Psectra diptera Hagen, 1866, Stett. Ent. Zeit., **27:** 376; Hagen, 1886, Ent. Amer., **2:** 21; McLachlan, 1868, Trans. Ent. Soc. Lond., **1868:** 170; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 44; Killington, 1936, Monogr. Brit. Neuropt., **1:** 247.

Hemerobius delicatulus Fitch, 1856, 1st and 2nd Rept. Ins. N. Y.: 96.

Psectra buenoi Navas, 1909, Ann. Soc. Sci. Brux., **33:** 218.

Head dark reddish brown, often black; antennae dark brown; thorax and abdomen dark brown, nearly black. Fore wing: length (average), 6 mm.; width, 3 mm.; membrane hyaline or pale yellow; gradates and other cross-veins margined with grey-brown; a few similar spots are scattered over the wing. Hind wing: when present, with markings similar to those of fore wing, but paler. Anal plates of male with the inner margin prolonged distally, forming a process which is armed apically with black bristles; ninth tergite with the lateral processes curved; tenth sternite in form of a curved, strap-like plate; parameres with the distal part strongly curved ventrally. Ninth sternite of female abdomen very short, rounded; eighth sternite with the dorsal margin prolonged anteriorly slightly into a short lobe.

Holotype (♂): near Leipzig, Saxony, Germany; in the Museum at Halle. The type has vestigial hind wings.

Distribution: This insect occurs over the northeastern United States, as far west as Michigan, and as far south as Virginia and West Virginia; it has been collected rarely in Ontario (Normandale, Mer Bleue). The adults have been taken from June through September. *Diptera* also occurs in Europe and Siberia, but it is not at all common anywhere. I have seen only 44 Nearctic specimens and Killington was able to locate records of but six from the British Isles.

This unusual Neuropteron has attracted a great deal of attention, especially in Europe, because of the occurrence of two winged individuals.[19] The lack of extensive series has caused some uncertainty as to whether or not the dipterous condition is restricted to one sex. Killington was led to believe that this dimorphism was not sexual at all and his conclusions are fully substantiated by the more extensive Nearctic material. Of the 44 specimens which I have seen 30 are females and 14 are males; 9 females and 9 males are dipterous. It may be, as these figures suggest, that a greater proportion of males than females are dipterous, but it is clear that both sexes may have the vestigial hind wings.

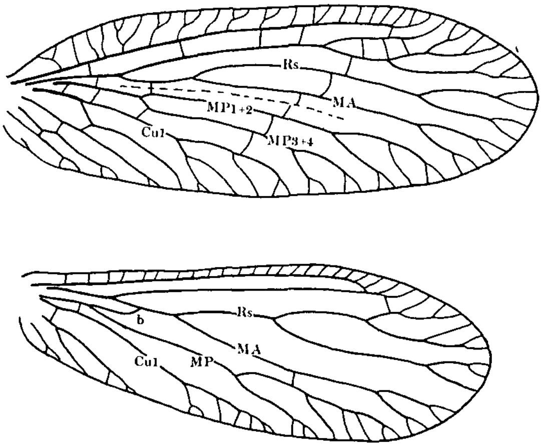

FIGURE 55. Wing venation of *Psectra diptera* (Burm.). Lettering as in figure 1.

The terminal abdominal structures (both sexes) of the Nearctic specimens are identical with those of the European individuals, which have been figured by Killington (1936, p. 248, fig. 64) and by Tjeder (1936, p. 99, fig. 1).

The synonymy of this species is clear. The two types of *delicatulus* Fitch are in the Museum of Comparative Zoology; they were examined by Hagen, who pronounced this species identical with *dipterus* (1886). *Ps. buenoi* Navas was based upon a 4-winged individual, the author not being aware that such specimens of *dipterus* had been recorded.

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[19] The most important papers on *Psectra diptera* not listed above are by Mjoberg (1909), Morton (1936), Killington and Kimmins (1932), Killington (1929), Kimmins (1935), Tjeder (1936).

Family Sisyridae

Antennae setaceous or nearly so, multisegmented, about half as long as the fore wing; basal segment enlarged; prothorax wider than long, but less so than in the Hemerobiidae; lateral margins not lobed; legs cursorial, coxae free, fore coxae very long; abdomen cylindrical; tenth tergite small in both sexes, with few trichobothria. Wings subequal, oval. Fore wing: costal space narrow, costal veinlets usually unbranched; recurrent humeral vein absent; Sc and R fused distally; Rs arising from R near the base of wing; MA coalesced with Rs for a short interval; free piece of MA usually absent; Rs with from one to three branches (not including MA). Hind wing: costal area very narrow, veinlets unbranched; MA coalesced with Rs for a long distance, the point of separation being near the middle of the wing.

The life history of some of the Sisyrids is fairly well known. The first important contribution to our knowledge of their biology was made by Needham (1901), who described the larva and pupa of the Nearctic species, *Sisyra vicaria* Walker (*umbrata* Needham) and *Climacia areolaris* Hagen (*dictyona* Needham). The following year Anthony published an excellent account of the morphology of the larva and pupa of *Sisyra vicaria* and more recently Old (1933) made a brief biological study of the larva and pupa of this species and *C. areolaris*. The most extensive study on the immature stages has been made by Withycombe (1923, 1925) on two British species of Sisyra.

The eggs of the Sisyridae are elongate-spheroid and are like those of Hemerobius except that the chorion is smoother. They are laid in clusters on leaves or twigs, etc., over fresh water, and are covered with silk. Incubation lasts about two weeks. On hatching from the egg the larva, according to Withycombe, drops into the water, forces its way through the surface film, and then floats along under water. Eventually, after reaching a sponge, it presses its mandibles into the body of the sponge and feeds on the body fluids. The first instar larva is very different from the two later ones; the jaws are short and stout, the antennae are 5-segmented, and tracheal gills are absent. In the second and third instars the mandibles are elongate and slender, almost bristle-like; the antennae are long and consist of about 15 segments and the first seven abdominal segments bear paired, leg-like tracheal gills ventrally. The larvae of the British species require the entire summer for development. When it is nearly ready to pupate, the larva leaves the water and crawls up a tree or similar object, where it spins a cocoon. This consists of two layers of silk, the outer one with a loose, wide mesh, and the inner one with a much denser texture. The British species hibernate in the prepupal stage, the pupa being formed in spring or early summer. The adults issue shortly thereafter.

So far as I am aware no insect parasites of the Sisyrids have been recorded specifically, though Old states that some of the pupae of Sisyra and Climacia which he obtained in Michigan contained hymenopterous parasites. Killington attributes the high mortality of the prepupae to infection by a fungus; on one occasion he found more than a thousand pupae so attacked.

The family Sisyridae has a wide distribution; it has been recorded from Europe, India, part of Asia, Africa, Australia, and North and South America. The two Nearctic genera of the family may be distinguished as follows:

Rs of fore and hind wings with one main fork, which is below the pterostigma; fore wing with dark brown and yellow markings ....Climacia (p. 254)
Rs of fore and hind wings with two main forks, both far proximal to the pterostigma; fore wing uniformly brown ....Sisyra (p. 253)

Genus *Sisyra* Burmeister

Sisyra Burmeister, 1839, Handb. Ent., **2** (3): 975; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 25; Killington, 1936, Monogr. Brit. Neuropt., **1:** 228.

Fore wing: broadly oval; costal area narrow at base, slightly widened beyond; subcostal area broad, with a basal cross-vein; R4 + 5 arising near the middle of the wing, R2 and R3 separating a short distance beyond; two or rarely three cross-veins between R1 and Rs; one between MA and Rs, and one between MA and MP1 + 2; MP forked just beyond separation of MA from Rs; no gradate series, the cross-veins being irregularly arranged.

Hind wing: Rs coalescing with MA for a longer interval than in the fore wing, separating from it at about the mid-wing and diverging towards R1; two main forks of Rs, both proximal of the pterostigma; MP forking just proximad of separation of MA from Rs; no gradate veins.

Terminal segment of labial palpi greatly enlarged; prothorax short; face very short, truncate. Tenth tergite of male very small, broader than long, entire; ninth tergite divided into two small, lateral plates, situated just anterior of and slightly below the tenth tergite; tenth sternite forming a broad, weakly sclerotized proximal plate, and a pair of short, heavily sclerotized claspers; hypandium internal, like that of Hemerobiidae; parameres small, not fused. Tenth tergite of female small, broader than long; eighth divided, short, but greatly extended ventrally; ninth tergite divided into a pair of large, ventro-lateral plates, to which is articulated the modified ninth sternite.

Genotype: *Hemerobius fuscatus* Fabr.

The genus Sisyra has as wide a range as the family to which it belongs; but only one species occurs in the Nearctic region.

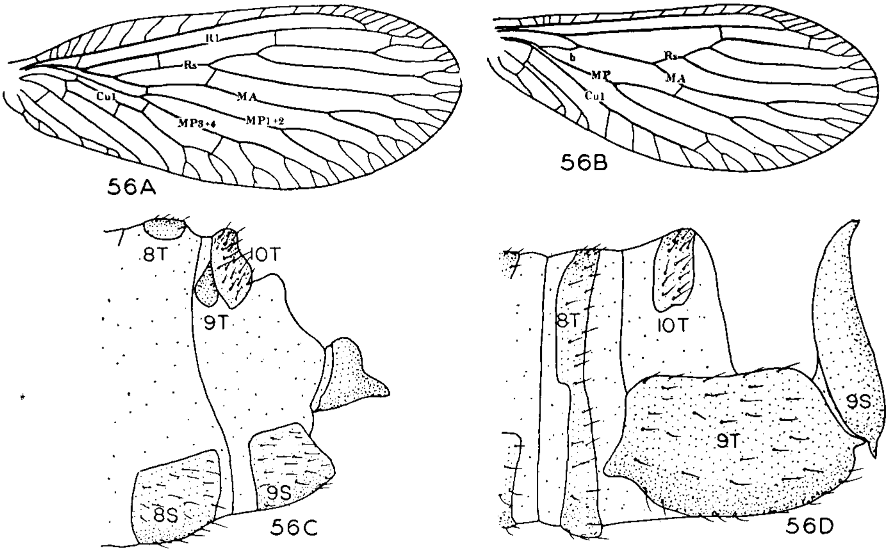

FIGURE 56. *Sisyra vicaria* Walker. A, fore wing; B, hind wing; C, terminal abdominal segments of male, lateral view; D, terminal abdominal segments of female, lateral view; 8T, 9T, 10T, abdominal tergites; 8S, 9S, 10S, abdominal sternites. Lettering of veins as in figure 1.

Sisyra vicarica Walker

Figure 56

Sisyra vicarica Walker, 1853, List Spec. Neuropt. Ins. Brit. Mus., **2:** 297; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 25.

Sisyra umbrata Needham, 1901, Bull. N. Y. State Mus., **47:** 555; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 25.

Sisyra lampra Navas, 1914, Bull. Brook. Ent. Soc., **9:** 60.

Head varying from yellow to brown; antennae light or dark brown, second segment very dark brown; legs yellow or very light brown; thorax yellowish brown to medium brown; abdomen brown. Fore wing: length (average), 6 mm.; width, 2.5 mm.; membrane uniformly light to dark brown, no wing markings. Hind wing: paler brown than the fore. Tenth sternite of male abdomen with large basal plate, claspers small, heavily sclerotized, the distal part conical and slightly curved. Ninth tergite of female abdomen very large, with the dorsal border nearly straight.

Types: two specimens (cotypes) from Georgia; in the British Museum of Natural History.

Distribution: NOVA SCOTIA (Anapolis Royal); QUEBEC; ONTARIO (Biscotasing; Go Home Bay); NEW YORK; MASSACHUSETTS; CONNECTICUT; PENNSYLVANIA (Ohio Pyle); MARYLAND (High Island); DISTRICT OF COLUMBIA; NORTH CAROLINA (Raleigh); GEORGIA; FLORIDA; ILLINOIS; MICHIGAN (Isle Royal; Detroit; Douglass Lake; Cheboygan Co.); WISCONSIN (Trout River); OREGON (Gold Hill, Jackson Co.); BRITISH COLUMBIA (Lilloeet, Agassiz, Kaslo); TEXAS (Colorado Co.). The adults have been collected from June through August. The foregoing records are decidedly discontinuous; the species probably occurs over all of the eastern states as far west as the Mississippi River; and across southern Canada into the northwestern states.

This is a very readily identified species. Needham's *umbrata* is beyond doubt a synonym of *vicaria,* as it has been regarded by Banks. When he described *umbrata*, Needham knew *vicaria* only by Walker's brief and unsatisfactory description; it is not surprising therefore that he found *umbrata* abundant in the field and in collections, though he could locate no specimens of *vicaria*, as he understood it. I have compared the two cotypes of *umbrata* in the Museum of Comparative Zoology with specimens of *vicaria* and have been unable to find any specific differences. Navas' *lampra*, based upon a single specimen from Lakehurst, New Jersey, is also *vicaria*. No figure accompanied the description of this insect but there is nothing included in Navas' description which indicates specific difference.

Genus *Climacia* McLachlan

Climacia McLachlan, 1869, Ent. Mo. Mag., **6:** 21; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 26.

Fore wing: slenderly oval; costal area very narrow, scarcely widened above the origin of Rs; costal veinlets widely spaced; subcostal area broad, with a cross-vein basally; R4 + 5 and R2 + 3 separating below the pterostigma; two or rarely three cross-veins between R1 and Rs; two between Rs and MA, and two between MA and MP1 + 2; MP forked at about the level of separation of MA from Rs; two short series of gradates.

Hind wing: Rs coalescing with MA for a considerable distance; furcation of M below origin of Rs, MA joining Rs much further distad than in Sisyra; R4 + 5 and R2 + 3 separating below the pterostigma; MP forked to level of point of separation of Rs from MA; usually one cross-vein between R1 and Rs, before pterostigma, two between MA and MP; the outer gradate series weakly formed.

Last segment of labial palpi only slightly enlarged; prothorax somewhat longer than in Sisyra; face much longer. Tenth tergite of male divided into two lateral plates; ninth tergite entire, short, and very broad; tenth sternite external, forming a pair of slender, lateral plates; ninth sternite small, entire; parameres partially fused, complex. Tenth tergite of female abdomen small, broader than long; eighth tergite consisting of two ventro-lateral plates; ninth tergite also composed of two ventro-lateral plates, somewhat larger than those of Sisyra; ninth sternite modified as in the latter genus and articulated to the ninth tergite.

Genotype: *Micromus areolaris* Hagen.

The immature stages of the species of this genus are similar to those of Sisyra.

Climacia is apparently restricted to the New World, but has been found in both North and South America. There is only one Nearctic species.

Climacia areolaris (Hagen)

Figures 57, 58; plate 3, figure 24

Micromus areolaris Hagen, 1861, Synop. Neuropt. N. A.: 199.

Climacia areolaris McLachlan, 1869, Ent. Mo. Mag., **6:** 21; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 26.

Climacia dictyona Needham, 1901, Bull. N. Y. State Mus., **47:** 558; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 26.

Head nearly uniformly yellow to light brown; antennae dark brown; thorax yellow to medium brown above, darker laterally; legs light yellow; abdomen dark brown. Fore wing: length (average), 5 mm.; width, 2 mm.; membrane yellow, at least slightly; markings light to dark brown; a brown patch present between Rs and the costal margin just before Rs, the pterostigma; another is present at the base between R1 and Sc; these two patches are often joined by a somewhat fainter brown streak; distal part of pterostigma usually with a very small dark brown spot; distal third of wing, exclusive of pterostigmal area is yellow-brown; just proximal to this the membrane is hyaline or nearly so; and proximal to this, is another yellow-brown area extending almost to the base; most all longitudinal and cross-veins are darker brown than the membrane. Hind wing: hyaline or nearly so; two brown spots, one at the distal end and the other at the proximal end of the pterostigma; veins only slightly darker than the mem-

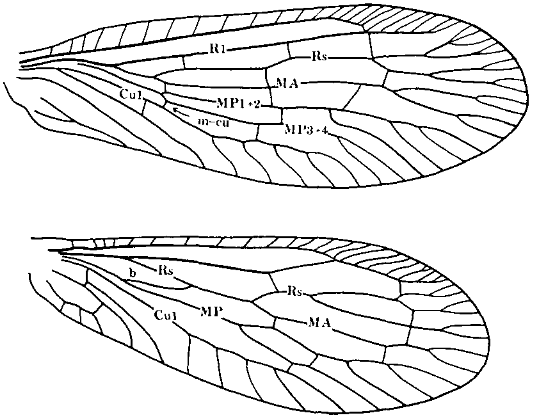

FIGURE 57. Wing venation of *Climacia areolaris* (Hagen). Lettering as in figure 1.

brane. Tenth tergite of male with the ventral border widened, prolonged distally; plates of tenth sternite almost strip-like, covered with coarse papillae, resembling fine teeth; ninth sternite with a pair of curved processes extending posteriorly on the inner surface; parameres forming a median plate, with a dorsal median lobe, that diverges abruptly from the plate. Ninth tergite of female very large with the dorsal margin prolonged anteriorly; tenth sternite much modified and articulated to ninth tergite.

Type: A single type of this species, from Florida (Osten-Sacken) was mentioned by Hagen. This specimen is not in the Museum of Comparative Zoology, where it should be; it was probably one of the several specimens destroyed when Hagen's collection was shipped from Europe to this country. The following male in the Museum of Comparative Zoology is therefore designated the neoholotype: Grant, Oklahoma, July 1, 1937 (Standish and Kaiser); in the Museum of Comparative Zoology. Allotype, by present designation: same collecting data; in the Museum of Comparative Zoology.

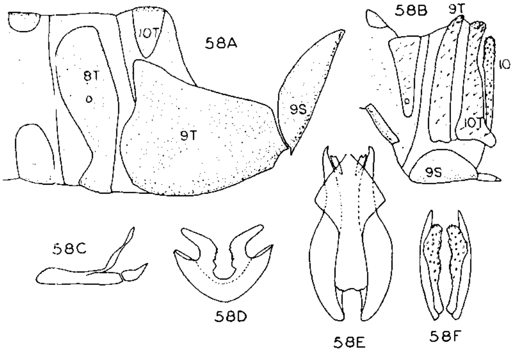

FIGURE 58. *Climacia areolaris* (Hagen). A, terminal abdominal segments of female (allotype), lateral view; B, terminal abdominal segments of male (neoholotype); C, parameres of same, lateral view; D, ninth sternite of same, posterior view; E, parameres of same, lateral view; F, tenth tergite and tenth sternite, posterior view. Lettering as in figure 56.

Distribution: QUEBEC; ONTARIO (Ottawa, Go Home Bay, Biscotasing); MAINE; NEW HAMPSHIRE; VERMONT; MASSACHUSETTS; CONNECTICUT; NEW YORK; PENNSYLVANIA; NEW JERSEY; MARYLAND; GEORGIA (Okefenoke Swamp); NORTH CAROLINA (Aberdeen); NEW MEXICO (Eddy Co.); VIRGINIA; TEXAS (Bosque Co.; Sutton Co.; Victoria); LOUISIANA (Shrevesport); FLORIDA; OKLAHOMA; MISSISSIPPI (Natchez); ILLINOIS; MICHIGAN (E. Lansing, Silver City, Douglass Lake, Burt Lake); OHIO (Put-in-Bay). This species probably occurs over all eastern United States as far west as the beginning of the plains region; it has extended beyond this area only at a few localities. It apparently does not reach the northwestern states or western Canada. The adults have been collected from June to October.

This striking and locally common insect is readily identified. As Banks has pointed out, Needham's *dictyona* is based upon individual characteristics only, such as size and the number of branches of Rs and the cubitus. I have examined the three cotypes of *dictyona* in the Museum of Comparative Zoology and have been unable to distinguish specific differences.

Family BEROTHIDAE

Antennae moniliform, multisegmented, first segment enlarged; antennae shorter than fore wing; ocelli absent; prothorax usually at least as long as wide, the lateral margins not lobed; legs cursorial; coxae well developed and free, the fore coxae especially long; abdomen slender, cylindrical; tenth tergite of male entire; aedeagus with a slender median sclerotized plate; ninth sternite well developed, external. Tenth tergite of female large, entire with a pair of conspicuous ventral processes extending anteriorly; ninth sternite small but usually strongly sclerotized.

Wings subequal; scales often present on veins of either or both fore and hind wings. Fore wing: costal area broader than that of hind wing, with forked veinlets; recurrent humeral veinlet usually absent;[20] Sc terminating on either R1 distally or the wing margin and joined to R1 by a cross-vein; Rs with four or more branches (not including MA), all arising from a single stem; MA coalesced with RS for a short distance proximally; a single series of gradate veins. Hind wing: costal area narrow, with unbranched veinlets; Rs and MA as in the fore wing; a single series of gradate veins; basal free piece of MA arranged as a cross-vein, not longitudinal as in most other Neuroptera.

The life history and general biology of the Berothids are almost entirely unknown. Tillyard, however, has described the egg and first instar larva of the Australian *Spermophorella disseminata* Till. and *S. maculatissima* Till. The elongate spheroidal

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[20] The recurrent humeral vein is present only in the aberrant *Naizeme patagonica* Navas, which may not be a Berothid.

eggs of these insects were laid in patches of 20 to 50 apiece and were stalked, as in the Chrysopidae. During oviposition the process of the tenth tergite was used as a lever to the end of the abdomen. The larvae, which hatched in about ten days, were long and slender, and crawled with the motion of a geometrid caterpillar, using the anal claspers in walking. The head was longer than that of the Hemerobiid larvae, the antennae were 4-segmented and the mandibles very nearly straight. The larvae did not survive in captivity beyond the first instar, presumably because of the lack of proper food. Tillyard was of the opinion that the larvae of these species inhabited the crevices of rocks and preyed on the lepidopterous larvae that fed on the lichens and moss. The larvae of the Nearctic Berothids are probably very similar to those of Spermophorella, since the adults are not greatly different. Smith (1923) obtained a single infertile egg from one of the Nearctic species (probably *Lomamyia banksi*, n. sp.); it was deposited directly upon the substratum, not stalked, but in all probability the manner of oviposition was abnormal.

The generic classification of the Berothidae in general is in a very confusing state.[21] Esben-Petersen pointed out in 1918 that the Berothidae "want a thorough revision." Krüger's unillustrated "monograph" of this family published a few years later (1922a) served only to make the confusion more nearly complete. Navas (1929) has published a better account of the Berothidae, but many of his concepts are based upon unique specimens or very small series and are consequently faulty. Thus, his attempt to separate the genera into two categories on the basis of the number of branches of the radial sector (5 or less, 6 or more) is not at all practicable because the number fluctuates in individuals beyond these limits. In order to determine the generic position of the Nearctic species, I have found it necessary to make a study of the Berothidae in general of all geographical regions. The results of this survey will be published elsewhere, since they are too irrelevant to the present revision for inclusion here. It is my conviction, however, that the genus Lomamyia, established by Banks (1904a) for the Nearctic species, is distinct from Berotha and therefore is a valid genus. Its relationship with other genera need not concern us here, since Lomamyia was the third genus of the family to be described and the other two (Isoscelipteron and Dasypteryx) are well established synonyms of Berotha.

Lomamyia differs from Berotha in having only three gradate veins in the hind wing, the lowest one being in line with the other two, i.e., slightly proximal to the one above it; also in having the gradate vein between MP1 + 2 and MP3 + 4 in the fore wing close to the one above it, usually not more than its own length away. In Berotha there are four or more gradate veins in the hind wing, the lowest being far proximal to the others; and the gradate vein between MP1 + 2 and MP3 + 4 in the fore wing is far proximal of the one above, usually at least five times its own length away. There seem to be no more than specific differences in genital structure exhibited by the members of these two genera; apparently the genera of Berothidae cannot be satisfactorily based upon genital structure, as in the case of the Hemerobiidae, for I have found the genitalia to be essentially the same in the Asian, Australian and Nearctic species of the family.

There are two striking characteristics of the Berothidae which deserve comment here: 1) In most species the outer margin of the fore wing is more or less incised below the apex. Krüger has used the presence or absence of this incision as the basis of the division of the family into subfamilies; but the extent of this incision is variable in all species and in certain ones the amount of variation is such that in a high percentage of specimens it is not possible to decide whether the incision is present or not (e.g., *longicollis* Walker). 2) A more interesting feature is the presence of scales on the wings and thorax of the females of certain species. McLachlan first called attention to these, on the wings of *B. fulva* Costa and of one Nearctic species.[22] Tillyard subsequently described these in full on the wing veins of *Spermophorella disseminata* Till. and *S. maculatissima* Till., but having interpreted incorrectly McLachlan's account, he made the presence of the scales on the veins the basis of the genus Spermophorella. The scales are also shown in the photograph of *Berotha neuro-*

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[21] One of the reasons for this is that the sexes have usually been confused in the past. In the Berothids it is the females instead of the males that have prominent external genital structures. Tillyard (1916) was the first to establish the fact that such specimens were females, for he was able to observe oviposition in Spermophorella; previous authors, as McLachlan, Hagen, Banks, etc., had assumed them to be males. Krüger (1922a) and Esben-Petersen (1917, 1918), both having overlooked Tillyard's paper, did likewise.

[22] McLachlan (1864) identified the species as *flavicornis* Walker, but this lacks the scales.

punctata Esben-Petersen (New South Wales), though no mention of them is made in the text. Of the Nearctic species more than half have scales present on the wings of the female. It is apparent, therefore, that these scales are of general occurrence among the Berothids and not restricted to a few species. Curiously enough, though the scales are on the upper side of the hind wing, they are present only on the lower side of the fore wing. Similar scales may also occur on the thorax and the legs of the females, as in *L. squamosa,* n. sp.

The Berothids have an unusual distribution: Australia, New Zealand, Africa, Japan, Hindustan, Ceylon, Formosa, Java, Borneo, eastern China (Shanghai), southeast Europe, Asia Minor, Argentina, United States and western Canada. The family probably has a much more extensive distribution than that at present known.

Genus *Lomamyia* Banks

Lomamyia Banks, 1904, Proc. Ent. Soc. Wash., **6:** 209; Navas, 1929, Mem. Acad. Cienc. Exact., Zaragoza, **2:** 25.

Fore wing: subtriangular, often elongate; costal area very narrow at base, usually much broadened above furcation of M, and narrowed near the middle of the wing; pterostigma present; two or rarely three cross-veins between R1 and Rs; usually five, rarely four or six, gradate veins, the one between MP1 + 2 and MP3 + 4 not more that its length from the one above it; MP3 + 4 is usually forked only to or slightly beyond the gradate vein between the branches of MP; Cu1 usually forked to outer cross-vein between Cu1 and MP3 + 4.

Hind wing: venation similar to that of fore wing; only three gradate veins, the lowest one only slightly proximal to that above it.

Prothorax much longer than broad; anal plate (tenth tergite) of male narrowed medially, with a long sclerotized process extending anteriorly from the lateral wings; aedeagus with a series of long bristles distally. Anal plate of female unspecialized; ninth sternite complex, with several sclerotized, short processes; eighth sternite with a pair of sclerotized processes extending forwards towards the seventh sternite.

Genotype: *Hemerobius flavicornis* Walker.

The characteristics on which the species of this genus may be classified differ greatly in the two sexes. The females are usually readily distinguished by the nature and distribution of the scales on the wings and thorax. In a few species (e.g., *flavicornis*) such scales are entirely wanting; in others they are present on the wings only (*occidentalis* Banks); and in still others they are in both wings and thorax. In using these characteristics, however, one must bear in mind that specimens in poor condition may have had the scales rubbed off wings and body. The process on the tenth tergite of the female varies considerably in length within the species and is of no use in specific taxonomy. The ninth tergite, however, is very different in most species, but it is very complex and needs careful orientation in the making of comparisons. The sclerotized rods of the eighth sternite also show marked difference in many species. The males are not so readily determined as the females. There being no secondary characteristics comparable with the scales, it is necessary to use venational and other features of the wings. Of particular interest is the presence of three cross-veins between R1 and Rs in two species (*squamosa* and *longicollis*). This is a characteristic which is also shared by Berotha and I was at first inclined to regard it as a basis for generic separation. However, since there are no other wing or body characteristics associated with the number of these cross-veins, I have treated the difference in number as specific only. The male genitalia, although having the sclerotized parts internal, provide excellent taxonomic characteristics, especially the aedeagus.

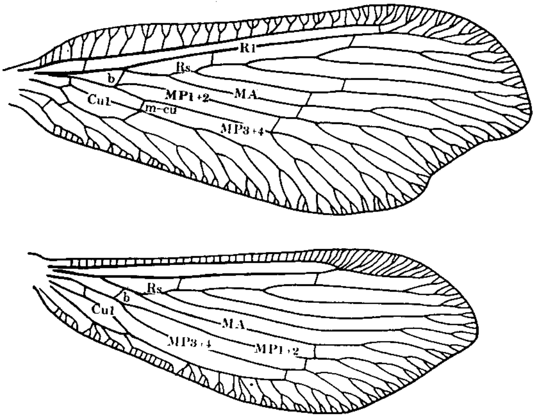

FIGURE 59. Wing venation of *Lomamyia flavicornis* (Walker). Lettering as in figure 1.

The genus Lomamyia is apparently restricted to the Nearctic region. Although many of our species have a wide distribution in this region, all are uncommon. Of the ten species which are known, I have been able to see only about 150 specimens. It is probable that many Nearctic species remain undescribed.

The males and females of this genus have been given separate keys, because of the ease with which the females may be determined by use of the secondary sexual characteristics.

KEY TO THE MALES OF NEARCTIC LOMAMYIA

1. Three radial cross-veins present, one directly below the pterostigma 2
   Two radial cross-veins present, none below the pterostigma 3
2. Apical border of fore wing deeply incised *squamosa*, n. sp. (p. 266)
   Apical border of fore wing entire or nearly so *longicollis* Walker (p. 267)
3. Four to six dark brown spots on costal area; costal area moderately broad 4
   Spots on costal area very weak or absent; costal area very narrow ......*hamata* Walker (p. 265)
4. Gradate veins of fore wing strongly margined, forming a distinct streak across the wing *texana* Banks (p. 264)
   Gradate veins at most weakly margined 5
5. Anterior margin of wing not concave, nearly straight ....*occidentalis* Banks (p. 263)
   Anterior margin of fore wing distinctly concave ..6
6. Fore wing very broad 7
   Fore wing narrow or at most only normally broad 8
7. Fore wing nearly uniformly yellow-brown, no maculations except on costal area; cross-veins not margined ....*fulva*, n. sp. (p. 264)[23]
   Fore wing nearly hyaline; numerous maculations present; gradate veins lightly margined *latipennis*, n. sp. (p. 262)
8. Fore wing very slender; apex strongly falcate *tenuis*, n. sp. (p. 261)
   Fore wing moderately broad; apex not falcate ...9
9. Face usually light yellow; aedeagus nearly straight *flavicornis* Walker (p. 259)
   Face usually brown or reddish brown; aedeagus strongly curved anteriorly *banksi*, n. sp. (p. 260)

KEY TO THE FEMALES OF NEARCTIC LOMAMYIA[24]

1. Scales present on fore coxae or at least a few veins of lower surface of fore wing 2
   Scales absent from coxae and fore wings 8
2. Scales absent from fore coxae 3
   Scales present on fore coxae 4
3. Fore wing slender, costal margin nearly straight, not concave ....*occidentalis* Banks (p. 263)
   Fore wing very broad, costal margin concave *latipennis*, n. sp. (p. 262)
4. Scales present on fore coxae only, absent from rest of thorax 5
   Scales present on fore coxae and also other parts of thorax 6
5. Costal area with four to six dark brown spots; gradate veins margined with dark brown; costal area broad ....*banksi*, n. sp. (p. 260)
   Costal area with very faint spots or entirely without them; gradate veins not margined; costal area very narrow ......*hamata* Walker (p. 265)
6. Scales on thorax confined to fore coxae and pleura of mesothorax; two radial cross-veins in fore wing 7
   Scales on fore coxae and pleural region of both meso- and metathorax; three radial cross-veins in fore wing ....*squamosa*, n. sp. (p. 266)
7. Fore wing slender, gradate veins heavily margined *texana* Banks (p. 264)
   Fore wing very broad, gradate veins not margined *fulva*, n. sp. (p. 264)
8. Two radial cross-veins in fore wing; none below the pterostigma .....*flavicornis* Walker (p. 259)
   Three radial cross-veins in fore wing, one below the pterostigma .....*longicollis* Walker (p. 267)

Lomamyia flavicornis (Walker)

Figures 59, 60; plate 3, figure 26

Hemerobius flavicornis Walker, 1853, List Spec. Neuropt. Brit. Mus.: 278.

Micromus flavicornis Hagen, 1861, Synop. Neuropt. N. A.: 198.

Lomamyia flavicornis Banks, 1905, Trans. Amer. Ent. Soc., **32:** 27.

Lomamyia nearctica Navas, 1913, Ent. Zeit., **27:** 19.

♂. Face and antennae yellow; vertex yellow, usually with several reddish brown spots; pronotum and mesonotum from yellow-brown to brown, usually with dark reddish brown spots at the base of the hairs; abdomen brown; legs pale yellow, very hairy, the tibiae spotted with dots of reddish brown; vertex, thorax, with long hairs, some brown, but mostly white. Fore wing: length (average), 9 mm.; width, 3 mm.; membrane hyaline; apex of the wing deeply incised; apex of the wing usually clouded with light grey-brown, sometimes extending as far as the gradate veins; costal area with four to six conspicuous dark brown patches; wings with long, brown and white hairs, the latter especially numerous; cross-veins with numerous very long, black hairs, especially well developed on the gradate veins; pterostigma usually reddish, at least in part; distal forks of branches of Rs and M usually marked with a small dark brown patch. Hind wing: hyaline, with dark brown maculations at the pterostigmal cross-veins and the gradate veins. Tenth abdominal tergite with two broad lateral plates, each giving rise to a long, anterior process and a short posterior process; the bridge between the two plates is extended posteriorly into a smoothly rounded lobe; sclerotized part of aedeagus forming a median strap-like structure, broadened anteriorly and terminating posteriorly in several very fine filaments; the anterior end of the aedeagus is only slightly curved, very nearly straight in lateral view.

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[23] The male of *fulva*, n. sp., is not known, but I have included the species in this key on the basis of the wing shape and markings, which do not differ in the sexes of Lomamyia.

[24] The female of *tenuis*, n. sp., is unknown.

♀. Like the male in size, coloration, without specialized hairs or scales on either wings or body.

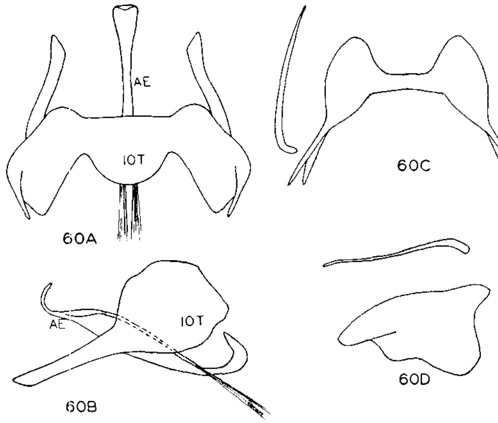

Figure 60. *Lomamyia flavicornis* (Walker). A, ninth sternite of male, dorsal view; B, same, lateral view; C, eighth sternite and lateral rods of seventh sternite of female, dorsal view; D, same, lateral view. AE, aedeagus; 10T, tenth tergite.

Eighth sternite strongly sclerotized; viewed ventrally there are two pairs of narrow posterior processes; the two lateral plates of the sternite are connected by a narrow sclerotized band; sclerotized rods of seventh sternite rather short.

Types: Two type specimens of this insect were mentioned by Walker: a, from "North America"; and b, from "Georgia" (Abbot); both are in the British Museum. The first specimen lacks the abdomen, but the wings are in good condition; they are heavily marked and agree with those of many specimens of the insect which has been identified as *flavicornis* by Banks and others in the past. This specimen is here designated the lectotype of *flavicornis*. The second specimen, b, is a different species; it apparently is the representative of variety "B" which Walker mentioned in his description. This is a female with scales on the fore coxae and is the species described below as *banksi*.

Distribution: FLORIDA (Winter Park, April 30, E. M. Davis; Tampa, E. P. Van Duzee); ALABAMA (Jackson, April 19, W. D. Pierce); GEORGIA (no further data); NORTH CAROLINA (Raleigh; Southern Pines; Tryon); VIRGINIA (Dead Run, Fairfax Co., August 6; Vienna, August); KENTUCKY (no further data); LOUISIANA (Caddo Park); MARYLAND (Glen Echo); NEW JERSEY (Prospertown); NEW YORK (Long Island); PENNSYLVANIA (Roxboro). Most of the specimens which I have seen lack complete collecting data; the meagre information available indicates that adults appear in early summer (April, May) and in the fall (August).

This species resembles *banksi* closely and has been confused with it in the past. The females of the two are readily distinguished, that of *flavicornis* lacking the scales on the fore coxae which are present in *banksi*. The males, however, are very difficult to separate without examination of the genitalia. Most specimens of *flavicornis* have broader wings than are usually found in *banksi*, but there seem to be no constant differences in wing markings. The aedeagus is strikingly different in the two, that of *flavicornis* being almost straight whereas that of *banksi* is strongly reflexed.

Nearctica Navas is almost certainly this species. The type locality of the unique male on which the species was based is Long Island, where both *flavicornis* and *banksi*, n. sp., have been collected. Navas' figure shows a much broader wing than I have seen in any specimens of *banksi*, though such wings do occur in many specimens of *flavicornis*. Navas himself synonymized his species with *flavicornis* in 1929.

Lomamyia banksi, n. sp.

Figure 61

♂. Face and antennae yellow; vertex greyish brown, with some dark reddish spots usually present; pronotum and mesonotum either yellow with reddish spots or medium reddish brown with faint spots; long black or dark brown hairs on vertex, thorax and legs, white hairs not usually conspicuous; legs pale, spotted with reddish brown and bearing long dark hairs. Fore wing: length (average), 10 mm.; width, 4.2 mm.; anterior margin concave, outer margin incised, much as in *flavicornis;* four to six dark reddish brown spots on costal area; membrane hyaline, maculations brownish, somewhat diffuse distally; gradate veins either with or without marginations; cross-veins with tufts of long black hairs; wing covered with dark brown hairs, white hairs usually not so abundant; two radial cross-veins. Hind wing: hyaline, with maculations at pterostigmal cross-vein and gradate veins. Tenth abdominal tergite with a pair of long anterior processes ventrally, and a pair of shorter anterior processes dorsally; lateral plates connected by a narrow sclerotized bridge; aedeagus long, the anterior part sigmoidally curved.

♀. Similar to the male in size and coloration; fore coxae with the anterior surface covered by a patch of appressed, black scales; rest of thorax and the wings without scales. Eighth abdominal sternite strongly sclerotized; a pair of short but distinct processes extending posteriorly and a pair of broader and flatter lobes on the anterior end, directed ventrally; sclerotized rods of seventh sternite very long and heavy.

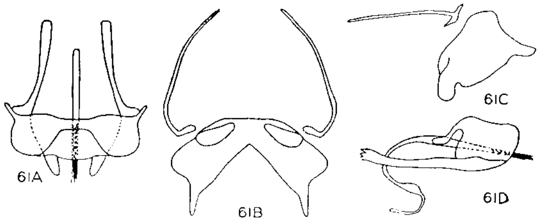

FIGURE 61. *Lomamyia banksi*, n. sp. A, tenth sternite of male (holotype), dorsal view; B, eighth sternite and lateral rods of seventh sternite of female (allotype), dorsal view; C, same, lateral view; D, tenth sternite of male (holotype), lateral view.

Holotype (♂): Clemson College, South Carolina; April 30, 1932 (D. Duncan). Allotype: same locality and collector, May 28, 1931. Both are in the Museum of Comparative Zoology.

Paratypes: 1♂, Falls Church, Virginia, September 3 (N. Banks); 1♀, Monticello, Florida, June 11, 1935 (G. Fairchild); 1♀, Nelson Co., Virginia, July 25, 1923 (W. Robinson); 1♀, Clemson College, July 23, 1936 (F. Sherman); 1♀, Manhattan, Kansas, October 5, 1934 (R. C. Smith); 1♀, Dobson, near Clarksville, Illinois, July 25, 1936 (Mohr); 1♀, Falls Church, Virginia, August 11 (N. Banks); all in the Museum of Comparative Zoology.—1♂, Wyandanch, Long Island, New York, July 15, 1917 (F. W. Schott); 1♀, Thomasville, Alabama, March 20, 1910 (W. D. Pierce); 1♀, Washington, D. C., July 26 (W. V. Warner); all in the United States National Museum.—1♀, Clemson College, South Carolina, May 9, 1932 (D. Duncan) in the Clemson College collection. 1♀, Manhattan, Kansas, October 5, 1934 (R. C. Smith); in the R. C. Smith collection.—1♀, Pike, Illinois, June 28, 1934 (Delong and Ross); 1♂, Anna, Illinois, June 27, 1909; both in the Illinois Natural History Survey collection.

Distribution: VIRGINIA (Falls Church; Nelson Co.); NORTH CAROLINA (no other data); SOUTH CAROLINA (Clemson College); FLORIDA (Monticello, Hilliard); ALABAMA (Jackson, Thomasville); MISSISSIPPI (Fulton, Hamilton); MISSOURI (no other data); DISTRICT OF COLUMBIA; NEW YORK (Long Island); KANSAS (Manhattan); ARIZONA (Santa Rita Mts.); ILLINOIS (Dobson, Pike, Anna, Jeff); MICHIGAN (Douglass Lake). The adults have been collected from May through July.

This species has been identified as *flavicornis* in the past. The females of *banksi* differ in possessing the patch of scales on the fore coxae; the males usually have somewhat narrower wings than those of *flavicornis,* and always have a sigmoidal aedeagus instead of a straight one, as in the latter.

Lomamyia tenuis, n. sp.

Figure 62

♂. Face and antennae yellow; vertex yellow with several distinct, dark brown or black spots, and a diffuse brown area medially; pronotum and mesonotum yellow and light brown, variegated; legs pale with several dark brown spots; vertex, thorax and legs with brown and white hairs; abdomen brown. Fore wing: length, 10 mm.; width, 3.8 mm.; very slender; costal area normally broad basally, but usually narrowed distally, the costal

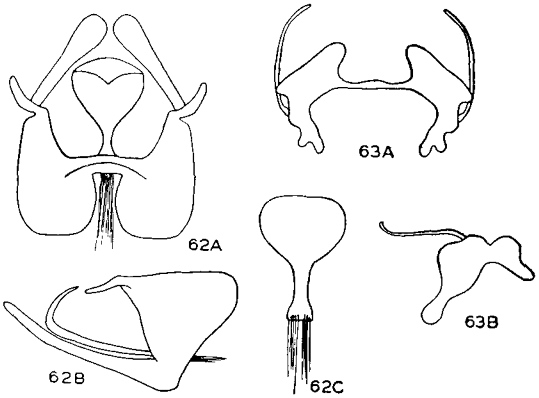

FIGURE 62. *Lomamyia tenuis,* n. sp. A, tenth sternite of male (holotype), dorsal view; B, same, ventral view; C, aedeagus, dorsal view.

FIGURE 63. *Lomamyia fulva,* n. sp. A, eighth sternite and lateral rods of seventh sternite of female (holotype), dorsal view; B, same, lateral view.

border being markedly concave; outer margin very deeply incised, the incision being posterior of the apex, forming a falcate tip; membrane hyaline; costal area with four (or more) dark brown spots; two radial cross-veins; maculations medium brown, in the form of small spots close together distally and posteriorly; gradate veins margined with brown. Tenth tergite with a pair of long ventral processes directed anteriorly and much flattened at their anterior end; a pair of shorter but conspicuous processes also directed anteriorly; the lateral plates connected by a narrow bridge; aedeagus greatly widened distally, more than in *texana*. Female unknown.

Holotype (♂): Torrance Co., New Mexico, July, 1925 (C. H. Martin); in the Museum of Comparative Zoology (donated by R. C. Smith).

This species, which resembles *texana* more than any other member of the genus, is distinguished from it by the more tenuous wing, the falcate apex, the less marked gradates, and the remarkably broad aedeagus.

Lomamyia latipennis, n. sp.

Figure 64

♂. Face and antennae light reddish brown; vertex similarly colored, with several small reddish spots and a dark reddish brown area medially; pronotum light reddish brown, somewhat variegated, darker medially; mesonotum light reddish brown, darker medially and laterally; vertex, pronotum and mesonotum with long dark brown hairs; legs pale spotted with dark reddish brown and with long grey-brown hairs; abdomen dark brown. Fore wing: length (average), 11 mm.; width, 5 mm.; costal area broad basally and only gradually narrowed, with 4–6 dark reddish brown spots; outer margin deeply incised; membrane hyaline, maculations light brown, darker and more diffuse distally, the membrane sometimes appearing nearly uniformly light brown; pterostigma reddish; two radial cross-veins; cross-veins not heavily margined; wing with dark brown hairs and a few black hairs at cross-veins. Hind wing: hyaline; pterostigmal cross-vein heavily margined, gradates not margined. Tenth sternite with a pair of long straight ventral processes, directed anteriorly; no posterior processes; aedeagus short and nearly straight, with a prominent tuft of black spines or stout hairs arising from the ventral surface of the aedeagus near the posterior end.

♀. Similar to the male in size and coloration. The fore and hind wings of the allotype bear only a few black scales, the others apparently having been rubbed off; the ♀ paratype has the scales of the fore wings on the proximal parts of MA and both branches of MP, as well as on the very basal part of Rs; and in the hind wings along Rs and MA in the region of the divergence of these veins. No scales are present on the coxae or rest of the thorax. The eighth sternite of the female abdomen is very broad and heavily sclerotized; a pair of lateral lobes extend posteriorly; two smaller lobes extend dorsally and laterally, and a pair of very large, flattened and broad processes are directed ventrally; rods of the seventh sternite are very weakly sclerotized.

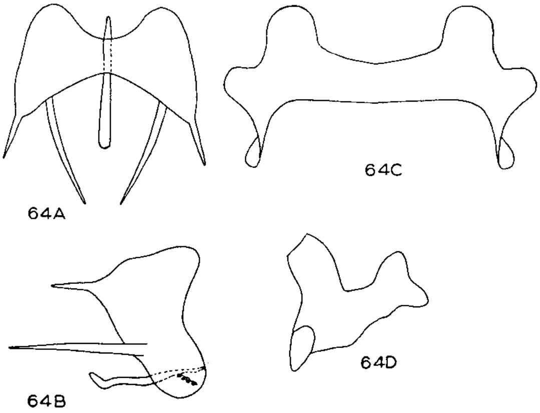

FIGURE 64. *Lomamyia latipennis,* n. sp. A, tenth sternite of male (holotype), dorsal view; B, same, lateral view; C, eighth sternite of female (allotype), dorsal view; D, same, lateral view.

Holotype (♂): Phoenix Lake, Marin Co., California, July 4, 1927 (H. H. Kiefer). Allotype: Mt. Tamalpais, Marin Co., California, May 23, 1909 (E. C. Van Dyke). Both are in the California Academy of Sciences.

Paratypes: 1♂, Cayton, Shasta Co., California, July 13, 1918 (E. P. Van Duzee); 1♀, Coleville, Mono Co., California, May 28, 1939 (M. A. Cazier); both in the Museum of Comparative Zoology.—1♂, Confidence, California, August 4 (J. N. Knull); in the Ohio State University collection.

This large Lomamyia is known to me only from California and Arizona. In addition to the types I have seen five other specimens: ♂, Cazadero, California, September 3 (E. P. Van Duzee); 2♂, Boulder Creek, California, July 18, 1933 (R. H. Beamer); ♂, Mt. Tamalpais, California, August 15, 1938 (L. W. Hopper); and 1♀, Yarnell, Arizona, July 29, 1933 (R. H. Beamer). The male of this insect resembles that of *flavicornis* superficially, but is at once distinguished by the much broader wings. The female is more like that of *occidentalis* Banks, in that both have scales on the wings but not on the coxae; the chief difference is found in the broad wings and concave anterior wing margin of *latipennis*. The male of *latipennis* is unique in possessing the tuft of black spines on the aedeagus; these are conspicuous enough to be seen without dissection of the abdomen. The female allotype has apparently had most of the scales rubbed from the wings; a few are visible at irregular intervals, however, which is enough to show that they actually were present. The female paratype, which has precisely the same genital structure as the allotype, has the scales more nearly completely attached.

Lomamyia occidentalis (Banks)

Figure 65

Berotha occidentalis Banks, 1905, Invert. Pacifica, **1:** 89.[25]

Lomamyia occidentalis Banks, 1905, Trans. Amer. Ent. Soc., **32:** 48.

♂. Face and antennae yellow; vertex yellow, with several spots of reddish brown; pronotum yellow, but with numerous reddish spots; mesonotum with a large dark reddish brown patch anteriorly, divided by a thin yellow stripe; rest of mesonotum yellow with several large and small reddish brown spots; abdomen medium brown; legs pale with red spots; vertex, thorax, abdomen and legs with long brown and white hairs, the latter especially conspicuous. Fore wing: length (type), 9–12 mm.; width (type), 4–5 mm.; costal area wide basally and not markedly narrowed beyond, so that the costal margin is very nearly straight; four to six dark reddish brown spots along the costal area; pterostigma reddish; two radial crossveins; membrane hyaline, with numerous small, light brown maculations, giving the wing a definitely spotted appearance; distally the maculations are larger and more diffuse; gradate series not margined; the wing with long brown and white hairs, and tufts of long black hairs on the crossveins. Tenth sternite with a pair of long, straight ventral processes, directed anteriorly and flattened distally; dorsal part of sternite with a pair of shorter processes also extending anteriorly; no posterior processes; aedeagus broad anteriorly, with the tip curved dorsally; posterior filaments in a single cluster.

♀. Similar to the male in size and coloration, but with scales as follows: in the fore wing, slender, subcylindrical scales on the lower branches of Rs, on MA and MP1 + 2. In the hind wing similar scales on the stem of Rs, but apparently not on its branches. Legs and thorax without scales. Eighth sternite of abdomen strongly sclerotized, with a pair of flat processes extending posteriorly and two rounded lateral lobes extending anteriorly; the two lateral plates connected by a thin bridge, with a slight median bulge; rods of seventh sternite very long and curved.

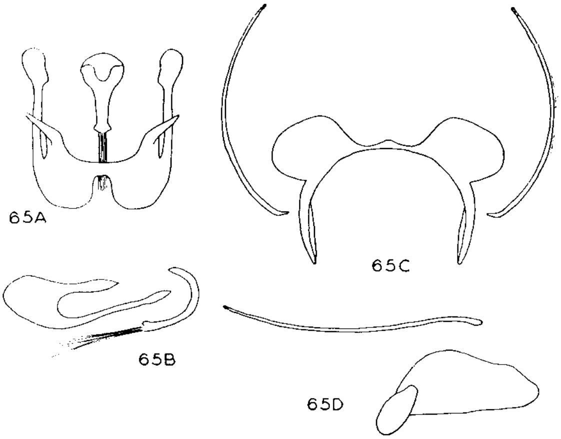

FIGURE 65. *Lomamyia occidentalis* (Banks). A, tenth sternite of male (allotype), dorsal view; B, same, lateral view; C, eighth abdominal sternite and rods of seventh segment of female (holotype), dorsal view; D, same, lateral view.

Types: two cotypes of this insect were mentioned by Banks, one (♀) from Ormsby Co., Nevada (C. F. Baker), and the other from Phoenix, Arizona. The former is the only one which I have been able to locate; it is in the Museum of Comparative Zoology and is here designated the lectotype. Allotype, by present designation: Clayton, California; July 20, 1935 (R. H. Beamer); in the University of Kansas Museum.

In addition to the types I have seen only two other specimens: ♀, San Diego, California, August 3, 1913 (E. P. Van Duzee); and ♂, Lytton, British Columbia, August 2, 1931.

This species is characterized by the spotted fore wings and the nearly straight costal margin, as well as by the presence of scales on the wings of the female. There is only a slight resemblance to

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[25] This species was listed by Banks in 1903 (Proc. Ent. Soc. Wash., **5:** 240), but was not described until 1905. The specimens mentioned in the 1903 paper were not those eventually taken as types.

latipennis and *fulva*. The male genitalia are closest to those of *texana*, but differ in several respects, such as having broader processes on the tenth sternite.

Lomamyia fulva, n. sp.

Figure 63

♀. Face and antennae yellow; vertex yellow, with numerous small, dark red spots; pronotum also mostly yellow, with some darker brown medially, which is continued on the meso- and metanota; all thoracic nota with small red spots; legs pale with a few red spots; vertex and thorax above with long grey-brown and dark brown hairs; legs with long light grey hairs; fore coxae and mesopleura with appressed black scales. Fore wing: length, 13 mm.; width, 6 mm.; very broad, as in *latipennis;* apex strongly incised; costal area moderately narrow, the margin concave; four to six brown spots along the costal area near the margin; wing membrane uniformly light yellow-brown; no maculations on the wing except for those on the costal margin and one at a cross-vein between Sc and R1; gradates not margined; black subcylindrical scales on MA, branches of MP and the proximal part of Cu, as well as the base of Rs; two radial cross-veins. Hind wing: membrane hyaline, with the pterostigmal cross-vein margined with dark brown; gradates not margined; black scales near the separation of MA from Rs. The eighth sternite heavily sclerotized, the two prominent, anterior lateral lobes directed slightly towards the middle of the segment; the posterior lateral processes are furcate distally; the bridge between the two lateral plates is very slender; rods of seventh sternite heavily sclerotized and moderately long.

Male unknown.

Holotype (♀): San Jacinto Mts., California, July 21, 1929 (R. H. Beamer); in the Museum of Comparative Zoology.

The female of this insect resembles that of *latipennis*, from which it differs by the presence of the black scales on the fore coxae and mesopleura. The male will probably be easily recognized by the wing coloring, especially the lack of marginations on the gradates.

Lomamyia texana (Banks)

Figure 66; plate 3, figure 25

Berotha texana Banks, 1897, Trans. Amer. Ent. Soc., **24**: 24.

Lomamyia texana Banks, 1905, ibid., **32**: 27.

♂. Face and antennae yellow; vertex yellow with several conspicuous dark reddish brown spots; pronotum and mesonotum medium brown, with similar reddish brown spots; abdomen dark brown; vertex, pronotum and mesonotum with a mixture of greyish brown and pure white hairs, the latter being very numerous; legs pale, spotted with reddish brown and bearing white hairs. Fore wing: length (average), 11 mm.; width, 4 mm.; slender, with the apex deeply incised; membrane hyaline; four to six dark reddish spots along costal border; pterostigma usually reddish; nearly all cells of the wing with a varying amount of light yellow brown, of greater density and extent in the distal part of the wing; gradate veins strongly margined with dark brown, forming an oblique streak across the wing; long hairs on the wing as in *flavicornis*, but white ones especially conspicuous; gradate veins with tufts of black hairs; two radial cross-veins. Hind wing: hyaline, the pterostigmal and gradate veins margined with brown. Tenth tergite with a pair of conspicuous anterior processes and a pair of short anterior lobes above; lateral plates of tergite connected by a narrow strip, lacking the prominent median posterior lobe of *flavicornis;* aedeagus short and straight, the anterior end being very broad and spatulate.

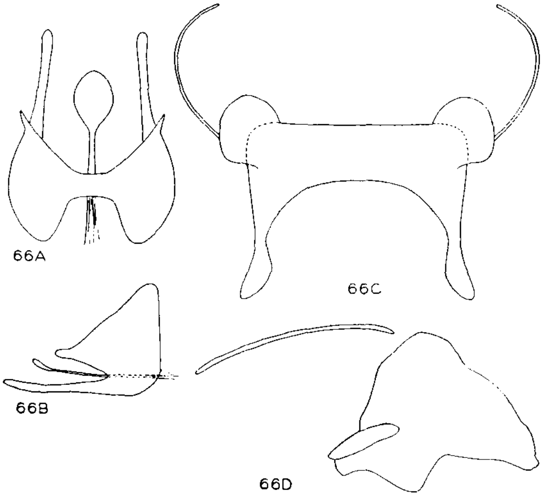

FIGURE 66. *Lomamyia texana* (Banks). A, tenth sternite of male (lectotype), dorsal view; B, same, ventral view; C, eighth abdominal sternite and rods of seventh sternite of female (allotype), ventral view; D, same, lateral view.

♀. Similar to the male in size and coloration, but with scales as follows: fore coxae with closely appressed black or dark brown scales; pleural region of mesothorax similarly scaled; fore wing with black or dark brown scales on the under surface of the two lower branches of Rs and on MA. Scales apparently absent from hind wing. The eighth sternite broad, heavily sclerotized, with a pair of lateral, posterior processes, and a conspicuous pair of rounded anterior lobes; sclerotized rods of preceding segment about as long as in *flavicornis* but somewhat more curved.

Types: Two males (cotypes) from Texas were mentioned by Banks and both are in the Museum of Comparative Zoology. One of these lacks the abdomen; the other is here designated the lectotype. Allotype, by present designation: Globe, Arizona, July 17, 1933 (Parker); in the Museum of Comparative Zoology.

Distribution: TEXAS (Comfort; Davis Mts., August 22, 1936, J. N. Knull); ARIZONA (Santa Rita Mts., May 31, E. E. Schwarz; Oracle, July 15, E. A. Schwarz; Globe, July 17; Oak Creek Canyon, August 15, 1938, J. N. Knull; Huachuca Mts., August 22, 1935, R. H. Beamer); UTAH (Bellevue, June 22, Spaulding; Parowan Canyon, Iron Co., July 16, 1919, Spaulding).

This species can usually be readily recognized by the dark oblique streak formed along the gradate veins. The female is further characterized by the possession of the patches of scales on the fore coxae and mesopleura. Several specimens of these females which I have seen had a waxy secretion covering the scales, which suggests that the scales may be associated with glands.

Lomamyia hamata (Walker)

Figure 67

Hemerobius hamata Walker, 1853, List Spec. Neuropt. Ins. Brit. Mus.: 278.

Micromus hamatus Hagen, 1861, Synop. Neuropt. N. A.: 199.

Lomamyia hamata Banks, 1905, Trans. Amer. Ent. Soc., **32:** 48.

Lomamyia hubbardi Banks, 1924, Bull. Mus. Comp. Zool., **65:** 430.

♂. Face and antennae yellow; vertex and thoracic nota also yellow, with scattered red spots; sides of prothorax and mesothorax reddish; vertex and pronotum without white hairs; abdomen yellow or light brown; legs pale yellow, spotted with red. Fore wing: length, 10 mm.; width, 4 mm.; costal space less than normally broad at base and much narrowed distally; pterostigma reddish; outer border of wing deeply incised, the apex being falcate; membrane yellow-brown, with some scattered faint brown maculations and with more conspicuous red maculations along the hind and apical margins; spots along the costal area absent or if present very faint and much reduced in size; two radial cross-veins; gradate veins not margined and apparently without tufts of hairs; the wing is covered with long, yellow-brown hairs. Hind wing: subhyaline, with the pterostigmal cross-vein heavily margined with dark brown. Tenth tergite of abdomen with a pair of long slender anterior processes ventrally and a pair of short anterior ones dorsally; lateral plates connected by a broad bridge; aedeagus very nearly straight and with only a slight thickening of the anterior part.

♀. Similar to the male in size and coloration; fore coxae with a patch of closely appressed black scales; fore wing with at least a few scattered black slender scales in the lower two branches of Rs and MA; hind wing apparently without scales. The eighth sternite with a pair of prominent lateral processes, somewhat twisted, extending posteriorly, and two lateral rounded lobes anteriorly, the two lobes being connected by a narrow bridge; sclerotized rods of seventh segment long and strongly curved.

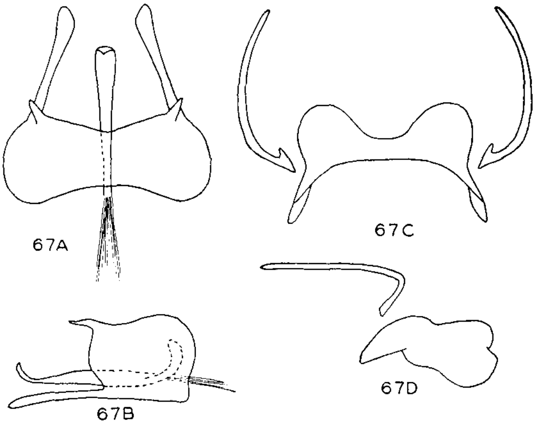

FIGURE 67. *Lomamyia hamata* (Walker). A, tenth sternite of male, dorsal view; B, same, ventral view; C, eighth abdominal sternite and rods of seventh sternite of female (allotype), dorsal view; D, same, lateral view.

Holotype (♂): "North America"; in the British Museum of Natural History. Allotype, by present designation: Tampa, Florida, May 2, 1918 (E. P. Van Duzee); in the California Academy of Sciences.

This distinctive species is known to me only by two specimens in addition to the type. One of these, the type of *hubbardi* Banks, is from Cedar Keys, Florida, April 5, 1878 (Hubbard and Schwarz); and the other is the allotype, from Tampa, Florida.

The male type of *hamata* lacks the abdomen, but the sex is clear from the absence of the scales on the coxae and wings. The fore wings of this insect are distinctive in having the spots along the costal margin absent or very weak, and in having a very narrow costal area. The type of *hubbardi* Banks, also a male, is identical with Walker's type in wing structure and coloration, and I am convinced that the species are the same, even though nothing is known of the genital structure of Walker's specimen. At the time when he described *hubbardi*, Banks was under the impression that *hamata* was a synonym of *flavicornis*. The female described above as the allotype agrees with the male from Cedar Keys, except for the scales on the wings and thorax.

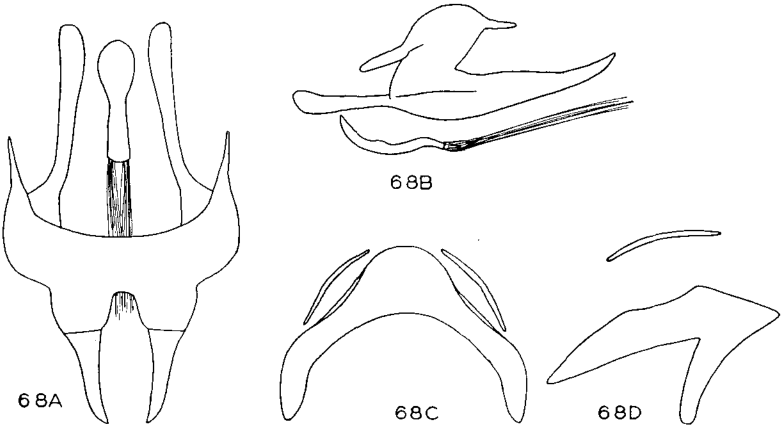

FIGURE 68. *Lomamyia squamosa,* n. sp. A, tenth abdominal sternite of male (holotype), dorsal view; B, same, lateral view; C, eighth abdominal sternite and rods of seventh sternite of female (allotype), dorsal view; D, same, lateral view.

Lomamyia squamosa, n. sp.

Figure 68

♂. Face and antennae yellow; vertex yellow, with small reddish spots at the very top; pronotum yellow with brown spots and a light reddish brown area medially; mesonotum yellow posteriorly, reddish brown anteriorly; vertex and thorax with pale yellow hairs; legs pale yellow, with red spots and yellow hairs. Fore wing: length (average), 9 mm.; width, 3.2 mm.; costal space broadened basally, narrowed near the middle of wing; outer margin smoothly and deeply incised, the apex falcate; membrane hyaline, with numerous light brown maculations, these being more or less diffuse in the distal half of wing; three radial cross-veins, one below the pterostigma; wing with dark brown or black hairs; gradate veins only slightly margined with brown and with only a few long black hairs; pterostigma reddish. Hind wing: hyaline, pterostigmal cross-vein strongly margined, gradate veins without marginations. Tenth tergite of abdomen with a pair of long ventral processes extending anteriorly and a short pair more dorsal, also directed anteriorly; a pair of prominent ventral processes extending posteriorly; aedeagus nearly straight, only slightly broadened anteriorly.

♀. Similar to the male except for the presence of black scales which are distributed as follows: fore coxae and most of fore femora; sides of pronotum; pleura of meso- and metathorax, and coxae and basal part of femora of meso- and metathorax. Also on fore and hind wing along the proximal parts of Sc, Rs, M, Cu. The eighth sternite of abdomen heavily sclerotized; seen in lateral view this forms an inverted "V"; seen from below, there is a median, posterior lobe, and two lateral arms, extending posteriorly; rods of seventh sternite much reduced.

Holotype (♂): Brownsville, Texas, June 11–16, 1933 (P. J. Darlington, Jr.); in the Museum of Comparative Zoology. Allotype: Sabinal, Texas, March 6, 1910 (F. C. Pratt); in the Museum of Comparative Zoology.

Paratypes: 1♀, Brownsville, Texas, June; 1♀, same, June 10 (H. S. Barber); both in the United States National Museum.—1♂, Brownsville, June (Snow); in the Museum of Comparative Zoology.

Distribution: This species is known to me only from Texas. In addition to the types I have seen specimens from Hildago Co., Cypress Mills, McAllen, and Devil's River (May 6). The insect appears to be not uncommon at Brownsville, from which I have seen six individuals.

This unusual Lomamyia is characterized by having a greater development of scales on the wings and thorax of the female than any of our other species of the genus. The male can at once be recognized by the presence of three radial cross-veins in the fore wing, one being below the pterostigma. *Longicollis* is the only other Nearctic Lomamyia which possesses the three radial cross-veins, and that species has the apical margin of the fore wing almost entire, not deeply incised, as in *squamosa*. Both male and female genitalia are unusual, though following the general pattern found in other species.

Lomamyia longicollis (Walker)

Hemerobius longicollis Walker, 1853, List Spec. Neuropt. Ins. Brit. Mus.: 281.

♂. Face and antennae yellow-brown; antennae a little stouter than in other specimens of the genus; vertex, pronotum and mesonotum brown, with some very dark brown or black hairs and many white ones; legs pale, spotted with dark brown and bearing many long white hairs; abdomen brown. Fore wing: length, 9 mm.; width, 4 mm.; apical margin not truly incised, at most slightly concave; costal margin nearly straight; costal area broad; pterostigma faintly reddish brown; four to six dark reddish brown spots along the costal border; membrane subhyaline, with numerous faint brown maculations which give the wing a brownish color, especially apically; veins dark, with little or no spotting; brown hairs on wing; three radial cross-veins, one below the pterostigma; gradate veins with tufts of black hairs, but not margined. Hind wing: no maculations or marginations of cross-veins. The structure of the male genitalia is not known; the only two males of this species which I have seen are the Walker types.

♀. Similar to the male; no scales on wings or thorax. The eighth sternite very small and so weakly sclerotized that it shows no definite shape, as it does in other species; there is no sclerotized plate. The rods of the seventh segment are very small.

Types: Two males (cotypes) from Georgia (Abbot); in the British Museum. Allotype, by present designation: Prattsburg, Georgia, July 25, 1930 (R. H. Beamer); in the Museum of Comparative Zoology (donated by R. C. Smith).

Distribution: In addition to the types I have seen but two specimens: ♀, from Ocean Springs, Mississippi; ♀, from Warren, North Carolina.

This species has been the cause of much uncertainty in the past. The lack of a definitely excised apical margin has made the generic position of the insect obscure. Walker's assignment of the insect to Hemerobius was of little significance, since the genus was then very loosely and broadly used. Hagen, on the basis of McLachlan's description, thought that the species was allied to the Sisyrid *Climacia areolaris* (Hagen). Banks in his revision of the Nearctic Hemerobiidae (1905) did not attempt to assign the species to any genus; subsequently, however, he obtained a specimen from Mississippi (Ocean Springs) and provisionally determined it as *longicollis*. My examination of the types in the British Museum shows that his identification was correct.

Although *longicollis* lacks the incised apical wing margin, an indication of it is present. The species is unusual for the lack, also, of the heavily sclerotized eighth abdominal sternite of the female, although there is a slight indication of this plate.

Family Polystoechotidae

Antennae setaceous or nearly so, short, less than half the length of the fore wing, first segment much enlarged; ocelli absent; prothorax much broader than long, not lobed laterally; legs cursorial, all coxae well developed and free; abdomen large. Tenth tergite of male entire, with well developed trichobothria laterally; ninth tergite narrow, the ventral margin extended slightly posteriorly; tenth sternite forming part of the internal armature; ninth sternite small. Tenth tergite of female entire, large; ninth narrow above, but extended so far ventrally as to almost envelop the segment; eighth sternite small.

Wings subequal; costal area at least slightly broadened above the separation of Rs from R1; Sc apparently terminating on costal margin; no true pterostigma present; Rs originating close to the base of the wing and giving rise to nine to fourteen branches, all of which fork several times; MA apparently coalesced with Rs, though there is no indication of the free basal part of MA; Cu1 forked close to the base of the wing. Hind wing: costal space narrower than that of fore wing; cross-veins unbranched; MA coalesced for a short interval with Rs at the base; free proximal part of MA distinct; Rs with from seven to thirteen branches; Cu1 forked close to base of wing.

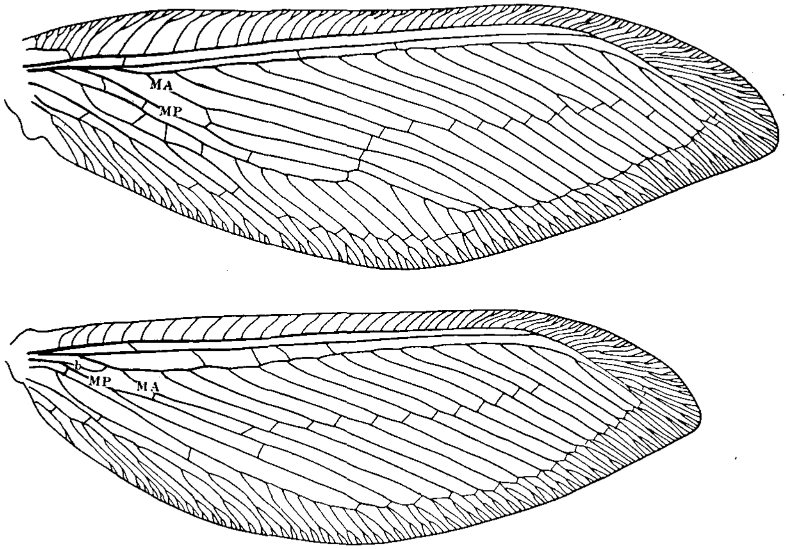

FIGURE 69. Wing venation of *Polystoechotes punctatus* (Fabr.). Lettering as in figure 1.

This family, which is confined to the New World, has in the past included only two genera, Polystoechotes Burm. and Fontecilla Navas (Chile);[26] a third genus is described in the present paper. Almost nothing is known of the immature stages of the Polystoechotids.

The two Nearctic genera now in the family may be distinguished as follows:

1. Costal area narrow at base, only slightly broadened beyond; abdomen slender *Polystoechotes* Burm. (p. 268)

   Costal area abruptly broadened at base, and very wide beyond; abdomen very stout *Platystoechotes,* n. gen. (p. 270)

Genus *Polystoechotes* Burmeister

Polystoechotes Burmeister, 1839, Handb. Ent., **2** (3): 982; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 28.

Fore wing: slender, pointed; costal area narrow at base and very slightly widened beyond; recurrent humeral vein present; costal veinlets forked; Rs with from eleven to fourteen branches; MA connected by a cross-vein to MP1 + 2 shortly after origin of the latter; two series of gradate veins, the outer with twenty-five to thirty cross-veins, the series close to the hind margin and nearly parallel to it; inner gradates with twelve to sixteen cross-veins. Hind wing: Rs having distinct contact with Rs; eleven to fourteen branches of Rs; MP forked at about the level of separation of MA from Rs; MP1 + 2 connected by a cross-vein to MA, shortly after the origin of Rs; two series of gradates, eighteen to twenty-three in the outer and ten to thirteen in the inner.

Eyes of moderate size; thorax narrow; abdomen very slender. Tenth tergite of male very large; ninth sternite with a long distal lobe; internal armature consisting of three complex, sclerotized plates; eighth sternite very long. Tenth tergite of female large; ninth narrow, but greatly extended ventrally; eighth sternite small but heavily sclerotized.

Genotype: *Semblis punctata* Fabricius.

The relationship of this genus with other Neuroptera is not at all clear. The genital structure, furthermore, is so unusual that I have been unable to homologize the parts with those of other genera in the order. Polystoechotes has been found in Chile (*P. gazullai* Navas), Panama, Mexico, and the Nearctic Region.

Polystoechotes punctatus (Fabr.)

Figures 69, 70; plate 3, figure 27

Semblis punctata Fabricius, 1793, Ent. Syst., **2:** 73.

Hemerobius nebulosa Fabricius, 1798, Ent. Syst. Suppl.: 202.

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[26] *Oliarces clara* Banks, from California, has been referred by Lameere (1936) to the Polystoechotidae, but a study of the type, which is the only known representative of the insect, has convinced me that this is not justifiable.

Hemerobius irroratus Say (nec Stephens), 1824, Long's Exped., **2:** 306; Fitch, 1856, 1st and 2nd Rept. Ins. N. Y.: 92.

Polystoechotes strictus Burmeister, 1839, Handb. Ent., **2:** 982; Walker, 1853, List Spec. Neuropt. Ins. Brit. Mus.: 231.

Osmylus validus Walker, 1853, ibid.: 233.

Hemerobius vittatus Say, 1824, Long's Exped., **2:** 307; Fitch, 1856, 1st and 2nd Rept. Inst. N. Y.: 93.

Polystoechotes punctatus Hagen, 1861, Syn. Neuropt. N. A.: 206; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 28.

♂. Lower face yellow or light brown; upper part, just below antennae dark reddish brown, sometimes nearly black; between vertex and antennae a thin transverse yellow band; vertex dark reddish brown or black, often variegated; vertex with conspicuous black and white hairs; antennae medium to dark brown; pronotum dark brown, with a small yellow irregular spot laterally; pronotum and mesonotum with black and white hairs, especially the latter; mesonotum brown, with some indication of reddish brown; metanotum and abdomen dark brown; legs light grey-brown, with light orange hairs; tip of tibiae and tarsal segments dark brown. Fore wing: length 18–34 mm.; width, 6–12 mm.; costal space only moderately broad; apex pointed, membrane hyaline or faintly smoky; costal area with dark brown spots; inner gradates margined; posterior part of wing with four to six large dark brown, irregular spots; also area between R1 and Rs and other parts of wing frequently with dark brown spots, very variable in intensity and size. Hind wing: hyaline; without markings except for a few light spots along outer gradates in the vicinity of Cu and M, ninth sternite with a median distal process; internal armature as shown in figure 70D.

♀. Like the male in color and markings, but usually larger, the fore wing length varying from twenty to forty millimeters. Ninth abdominal sternite strongly sclerotized; seen from below the plate shows a posterior median lobe distally excised; a pair of lateral plates extending dorsally; and between these vertical plates a heavily sclerotized rod extending anteriorly and attached to the ninth sternite by a membrane.

Type: Without locality data; in British Museum.

Distribution: This is a very widely distributed insect. I have seen specimens from all of the states west of the Rocky Mountains (approximately longitude 105°); and from Georgia, New York, New Hampshire, Maine, Massachusetts, Pennsylvania, Maryland and North Carolina. It is common in British Columbia, Alberta, Ontario, and Quebec. Hagen reported it from Texas and although I have seen no specimens from that state, I have no doubt it does occur there. In the collection of the California Academy of Sciences there is a specimen from Lower California; and in the Museum of Comparative Zoology there is a female from Panama (Lino). The most northern record is near Peace River (town), Alberta (lat. 56°). The species is far more common in the western states (especially the northern ones) than it is in the eastern. Of particular interest is the fact that *punctatus* seems to be absent from the prairie states and Manitoba. The adults appear in June and persist until the end of October. They are positively phototropic and during the fall, especially

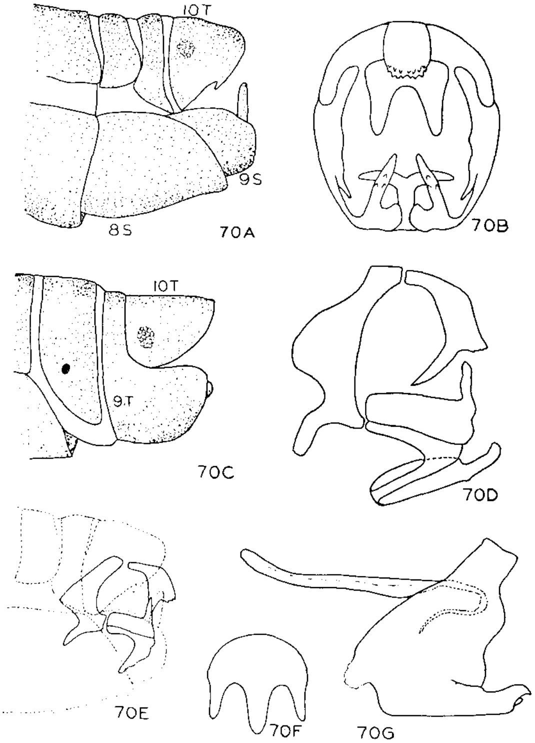

FIGURE 70. *Polystoechotes punctatus* (Fabr.). A, terminal abdominal segments of male, lateral view; B, same and internal armature, posterior view (ninth sternite omitted); C, terminal abdominal segments of female, lateral view; D, internal armature of male, lateral view; E, same, showing position of parts with reference to segmentation; F, ninth sternite of male, ventral view; G, ninth abdominal sternite of female, lateral view.

August, a great many individuals may be collected at lights in the western states.[27] I have seen more than five hundred specimens.

Punctatus is remarkable for its variability in size. This, in conjunction with a similar instability in the color pattern of the wing, has been the chief cause of the many synonyms. Fabricius' description of the insect was too incomplete to enable recognition of the species from that alone. Hagen saw the type in the British Museum and of course readily recognized the insect. He was also able to see the types of most other synonymous species, all of which were described before the publication of his "Synopsis of the Neuroptera of North America" in 1861.

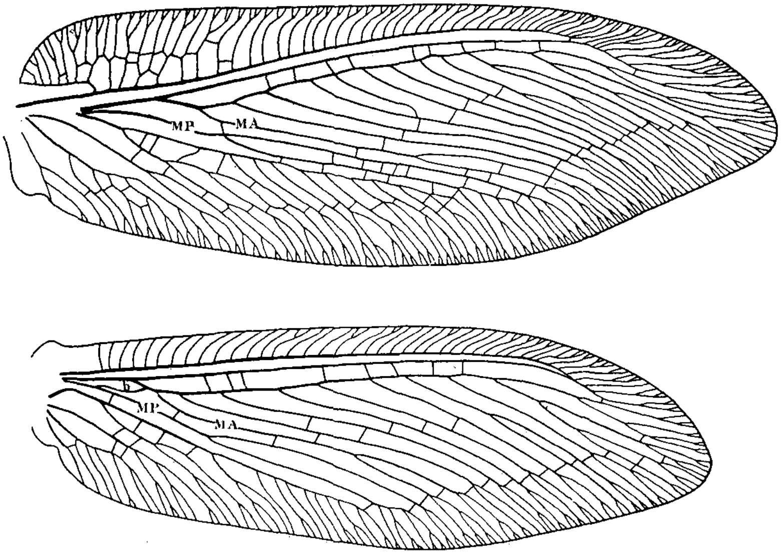

FIGURE 71. Wing venation of *Platystoechotes lineatus*, n. sp. Lettering as in figure 1.

The most surprising fact about *punctatus* is that in spite of its large size and local abundance, its immature stages are almost unknown. Needham (1901), Hungerford (1931) and Welch (1914) have obtained eggs from captive specimens. The larvae obtained by Welch lived only a few days, presumably because of the lack of proper food. The eggs were laid singly, were oval, white and very granular. They were exceedingly small, being less than a millimeter in length. The incubation period was found by Welch to be ten days. The newly hatched larvae were about 1.5 mm. long, slender and tapering, and had a very large head. The mandibles were straight; the antennae were 8-segmented, the first and second segments much larger than the others; the maxillary palpi were 5-segmented. Welch was of the opinion that the larvae were predaceous and terrestrial; Needham suggested the possibility of their being terrestrial or arboreal; Hagen that they were aquatic; and Banks that they were parasitic on an aquatic insect.[28] Whatever the environmental occurrence of *punctatus* may be, it is obvious that the mature larva, which must be at least an inch in length, has not been found.

Genus **Platystoechotes,** n. gen.

Fore wing: slender, costal area abruptly broadened at base; humeral recurrent vein present; costal veinlets forked, the proximal ones joined by cross-veins; Rs with eight to twelve branches; MA joined to MP by a cross-vein at about the fork of MP; two series of gradate veins, the outer one with 28–35 cross-veins, the series remote from the margin and forming a broad "V"; inner gradate series with 9–11 cross-veins.

Hind wing: Rs having slight contact with MA; Rs with seven to nine branches; MP not forked nearly as far proximally as the separation of MA from Rs; MA connected to MP before furcation of latter; two series of gradates, 11–14 in the outer, 6–8 in the inner.

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[27] Fyles records (1903) the occurrence of a cloud of these insects above a warehouse in Ontario; the aggregation was so dense that observers mistook it for smoke and called out the fire-engines.

[28] Lestage (1925) and Withycombe (1925) have discussed these possibilities at some length, without coming to a definite conclusion.

Eyes small; thorax broad and thick, the head recessed into the prothorax; abdomen very thick. Tenth tergite of male large; ninth tergite of moderate size; tenth sternite forming part of the internal armature; ninth sternite small; eighth large; internal armature consisting of two complex plates. Tenth tergite of female large rounded; ninth tergite narrow but extended ventrally; ninth sternite divided; eighth sternite small and heavily sclerotized.

Genotype: *Platystoechotes lineatus*, n. sp.

This genus is related to Polystoechotes. The wings are much like those of *punctatus,* though having a much broader costal area. The wings alone, however, would not justify the erection of a new genus, but the terminal abdominal segments of the male and female of *lineatus* are so different from those of *punctatus* that I have not been able to homologize the parts satisfactorily. It is because of the difference in genital structure that I have considered a new genus necessary.[29]

Platystoechotes lineatus, n. sp.

Figures 71, 72; Plate 3, figure 28

Clypeus yellow; frons reddish brown and yellow, variegated; vertex from light to dark reddish brown, with some yellow usually present just behind the eyes laterally; vertex with long white hairs; antennae yellowish; pronotum reddish to medium brown, with very long grey-brown hairs; meso- and metanotum medium brown, with grey-brown and white hairs; abdomen light reddish brown, with brown hairs. Fore wing: length, 25–28 mm.; width, 8–9 mm.; costal area very broad; cross-veins present between the costal veinlets in the proximal half of the wing; membrane hyaline; costal area with 4–6 large brown spots; numerous smaller spots between R1 and Rs; a wide transverse brown band from the hind margin to R1 at about mid-wing; a thinner but slightly darker stripe follows along the line of the gradates; long hairs are present on all veins, brown ones on the brown areas and white ones on hyaline areas. Hind wing: hyaline, but with the outer and most of the inner gradates surrounded by a dark brown spot, the gradate veins themselves being white. The terminal abdominal segments as described for the genus; internal armature consisting of a very weakly sclerotized structure in the form of a "C," when seen in side view; in end view the structure is seen to be composed of a dorsal median piece and two lateral divergent arms, supporting ventrally a median posterior process.

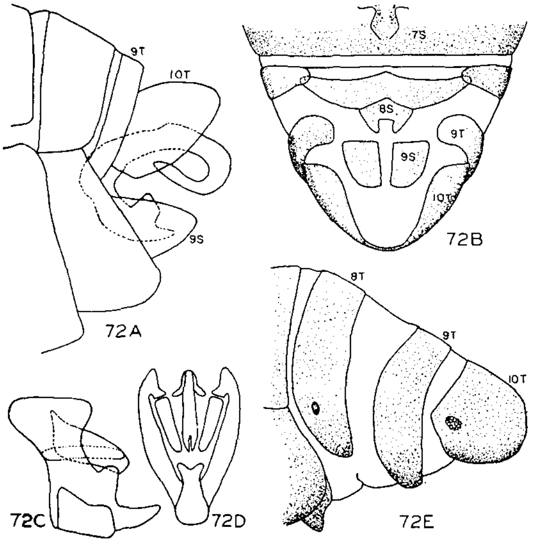

FIGURE 72. *Platystoechotes lineatus,* n. sp. A, terminal abdominal segments of male (holotype), lateral view; B, same of female (allotype), ventral view; C, eighth abdominal sternite of female, lateral view; D, ninth abdominal sternite and internal armature of male, posterior view; E, terminal abdominal segments of female, lateral view.

♀. Similar to the male in color, but usually larger, the fore wing varying from 25–33 mm. Eighth sternite strongly sclerotized ventrally and bearing two vertical, lateral plates; between the latter a short, heavily sclerotized rod; ninth sternite with a conspicuous median depression posteriorly, with a pair of prominent teeth projecting inwards near the posterior end of the depression.

Holotype (♂): Wolverton, Sequoia National Park, California, 7000–9000 ft., June 14, 1929 (E. C. Van Dyke); in the California Academy of Sciences. Allotype: same locality, June 13, 1929 (E. C. Van Dyke); in the California Academy of Sciences.

Paratypes: 1♂, same locality as holotype, June 19, 1929 (E. C. Van Dyke); 1♀, same, June 24,

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[29] Navas' monospecific genus Fontecilla (1931), from Chile, has a broad costal area, somewhat like that of *lineatus,* but the wings are falcate apically. Since Navas did not describe the venation of his insect (*F. graphicus* Nav.), no venational comparisons between Platystoechotes and Fontecilla can be made. The type of *graphicus* was originally in the Navas collection, and I have been unable to ascertain its present location.

1929; 1♀, Norval Flats, Lassen Co., California, 5500 ft., June 2, 1920 (J. O. Martin); all in the California Academy of Sciences.—1♂, Wolverton, California, June 19, 1929 (E. C. Van Dyke); 1♀, Potwisha, Sequoia Nat'l. Park, 2–5000 ft., California; 1♂, Giant Forest, Tulare Co., California, July 15, 1928 (C. L. Fox); all in the Museum of Comparative Zoology.—1♀, Giant Forest, California, July 28, 1929 (R. H. Beamer); in R. C. Smith collection.—1♂, 1♀, Glacier Pt., 7214 ft., California, June 13, 1931; in the University of California collection.

This striking insect, which has so far been found only in California, is readily recognized by the wing markings and shape, as well as by the very stout body. It is surprising that such a large and conspicuous insect as this has not previously been described and that it was not collected prior to the past twenty years. It is apparently not rare in Sequoia National Park and vicinity, where, I am informed, it is taken without much difficulty by students at the University of California. The general habitus of this insect is very different from that of *punctatus;* the latter has a slim, elongate abdomen, whereas *lineatus* has an exceedingly stout one. Since this is true of both sexes, the size of the abdomen in the female can hardly be due to the presence of an unusually large number of eggs. It is greatly to be hoped that some attention will be given to the life history of this insect.

Family Dilaridae

Antennae filiform in the female, pectinate in the male; first segment enlarged; functional ocelli absent, but three ocelli-like pilous tubercles are present; prothorax as wide as long, usually broader and bearing several conspicuous tubercles; its lateral margins not lobed; legs cursorial; coxae large and free; abdomen cylindrical and short; tenth tergite of male transverse, with trichobothria; tenth sternite forming part of the internal armature; female with a long ovipositor.

Wings subequal, very hairy, often showing sexual dimorphism. Fore wing: costal space either narrow or broad, but never abruptly widened at base; recurrent humeral vein absent; cross-veins numerous in costal area, mostly unbranched; all branches of Rs arising from a single stem; Rs with from two to five branches arising directly from the stem; MA either coalesced with Rs or coalesced with R and separated from it before origin of Rs; MP either deeply forked or twigged at the margin of the wing; cross-veins few or many, rarely arranged in gradate series.

Hind wing: costal space narrow, with numerous unbranched cross-veins; MA usually coalesced with Rs, though rarely free; MP usually deeply forked; Rs with from two to five branches; cross-veins few or many, rarely arranged in gradate series.

Nothing is known of the immature stages of the Dilaridae. The suggestion has been made that the larvae are aquatic, but as Hagen pointed out this does not seem likely in view of the long ovipositor. In this connection it is pertinent to note that Dr. W. H. Anderson has recently reared a male of the Nearctic species, *Nallachius americana* (Hagen) from wood debris of a dead tulip tree (*Liriodendron tulipifera* Linn.), near Falls Church, Virginia. The wood had been collected a few weeks before from the tree, which stood near the edge of a wooded area about 300 feet from a small stream. It seems very probable that the pupa of the insect was secreted on or in the dead wood.

This family is an exceptionally interesting one. Although the species exhibit various specializations, such as the pectinate antennae of the male, some possess characteristics which are clearly generalized. In this category, for example, is the free MA which occurs in *Dilar corcyracus* Navas. The existing species of the family are undoubtedly but a small remnant of a much larger group. Navas was led to conclude from a revisional study of the family that several genera exist, rather than Dilar alone, and I believe that most of the six new genera which he described are valid. Although only about thirty species of Dilaridae are known, the family has a wide distribution: Asia, Europe, Africa, and North and South America. Most of the genera, however, are restricted to single continents. Only one genus occurs in the Nearctic region.

Genus *Nallachius* Navas

Nallachius Navas, 1909, Mem. Real. Acad. Cienc. Artes Barc., **7:** 666.

Fore wing: slenderly oval in female, subtriangular in male; costal area very narrow for its entire length; pterostigma weakly formed; at least one cross-vein between R1 and Rs; gradate veins absent or few in number; Rs with two or three branches arising directly from stem Rs; M coalesced with Rs for a considerable distance, and apparently also coalesced with Rs, which arises as an anterior branch of MA near the mid-wing; basal piece of MA usually present at base of wing, often obsolescent; Cu1 deeply forked.

Hind wing: elongate-oval in female; broadly oval in male; costal area narrow; Rs with two branches from stem Rs; one or two cross-veins between R1 and Rs; MA coalesced with Rs for a considerable distance, also apparently with R4 + 5; free part of MA obsolescent; MP forked to level of separation of MA from stem Rs.

Antennae of male with from 12–16 segments; of female with from 15–17 segments; prothorax much broader than long; tenth tergite of male divided, forming two lateral plates, with numerous trichobothria; ninth tergite entire, the ventral margin extended posteriorly; eighth tergite entire and very short, but extending nearly to ventral part of segment; ninth sternite small; eighth larger; tenth straight and apparently forming a complex armature, consisting of an anterior transverse plate, with two pairs of posterior processes, one pair lateral, the other medial; hypandrium small. Female with the ovipositor curved strongly over the abdomen.

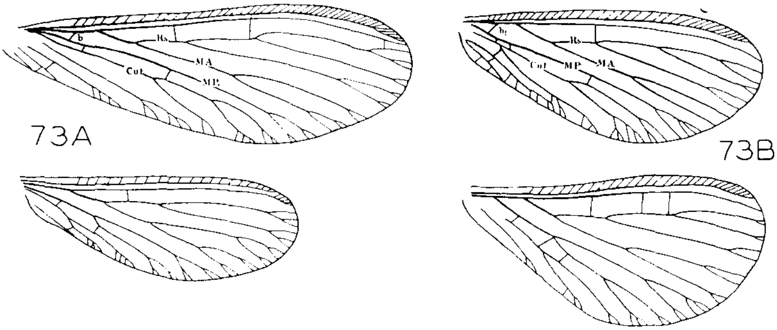

Figure 73. Wing venation of *Nallachius americana* (McLachlan). A, female (holotype); B, male (allotype). Lettering as in figure 1.

Genotype: *Dilar prestoni* McLachlan.

This small genus includes four species: *prestoni* McLach. from Brazil; *loxanus* Navas from Equador; *pulchellus* Banks from Cuba and Arizona, and *americanus* McLachlan from Kentucky and Virginia.[30] The two latter species may be separated as follows:

1. Fore wing without a series of gradate cross-veins *americanus* McLach. (p. 273)
   Fore wing with a series of gradates *pulchellus* Banks (p. 274)

Nallachius americanus (McLachlan)

Figures 73, 74

Dilar americana McLachlan, 1881, Ent. Mo. Mag., **18:** 55; Banks, 1905, Trans. Amer. Ent. Soc., **32:** 24.

Nallachius americanus Navas, 1909, Mem. Real. Acad. Cienc. Artes Barc., **7:** 669; 1914, Gen. Ins., fasc. **156:** 11.

♂. Head, first antennal segment, prothorax and abdomen reddish brown; ocellar warts light brown; antennae and legs pale yellow. Fore wing: length, 4 mm.; width, 1.8 mm.; membrane either hyaline or slightly greyish; maculations grey, in the form of large, irregular spots, sometimes very diffuse, so that the entire wing is more or less grey; veins with long grey hairs. Hind wing: length, 3 mm.; width, 1.8 mm.; very broadly oval, color as in fore wing. Anal plates (tenth abdominal tergite) with a short, broad tooth arising from the posterior margin near the mid-point; internal armature with the lateral processes longer and straighter than the inner pair; aedeagus only about half as long as latter.

♀. Head, thorax and abdomen pale brown; antennae and legs yellow. Fore wing: length, 5 mm.; width, 2 mm.; elongate oval; membrane hyaline, with numerous grey maculations as in the male. Hind wing: length, 3.5 mm.; width, 1.5 mm.; color as in the fore wing.

Holotype (♀): Bee Spring, Kentucky, June, 1874 (Sanborn); in the Museum of Comparative Zoology. Allotype, by present designation: about 4 mi. northeast of Falls Church, Virginia, on the property of R. A. Cushman; the specimen emerged from woody debris of a dead tulip tree, May 25,

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[30] There are also undescribed species in the Museum of Comparative Zoology from Paraguay and Puerto Rico.

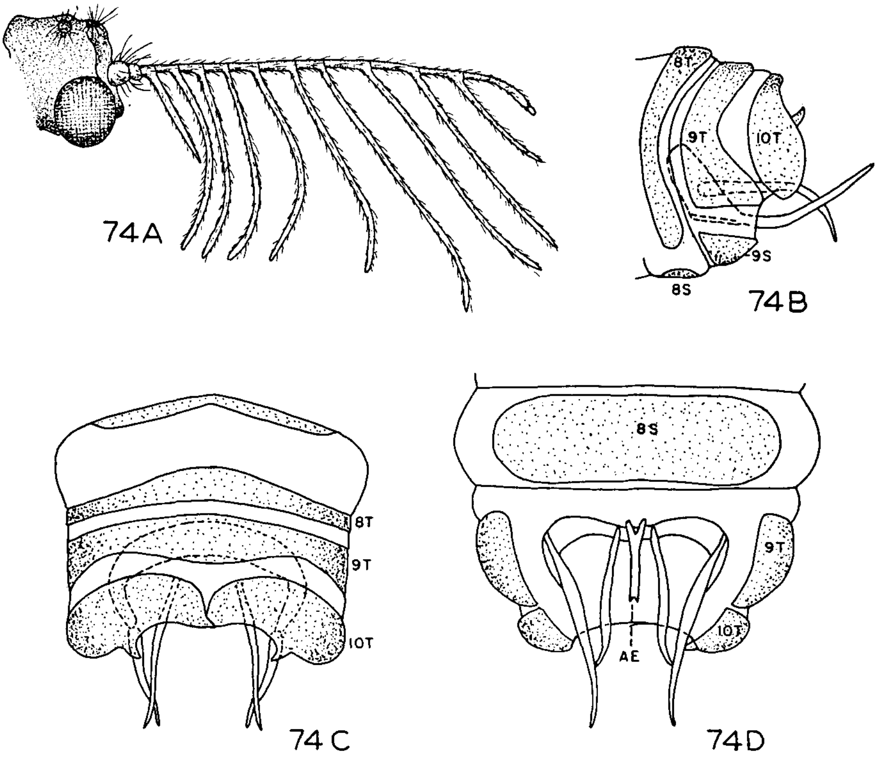

FIGURE 74. *Nallachius americana* (McLachlan), male (allotype). A, head and antenna, lateral view; B, terminal abdominal segments, lateral view; C, same, dorsal view; D, same, ventral view (ninth sternite omitted). Lettering as in figure **2**.

1939 (W. H. Anderson); in the United States National Museum.

I have seen only three specimens of this rare insect in addition to the types mentioned. One of these (♂) was collected at Glen Echo, Maryland, July 16, 1922 (J. R. Malloch) and is in the National Museum. The other two (♂, ♀) were collected at Falls Church, Virginia, July 20, on the same tree and within a few minutes of each other (N. Banks); these are in the Museum of Comparative Zoology. In the latter male, from Falls Church, the wings are greyish, without definite spots, the maculations apparently being diffuse. The genitalia of this specimen are identical with those of the allotype. The wing venation probably varies considerably in this insect. The holotype specimen has three branches of Rs arising directly from stem Rs in the fore wings, whereas all other specimens have only two. The male antennae appear to differ markedly in the several genera of Dilarids, but they also show some individual variation. One of the males of *americana* (allotype) has two more antennal segments than are present in the other male.

Nallachius pulchellus (Banks)

Figure 75

Dilar (*Nallachius*) *pulchellus* Banks, 1938, Rev. de Ent., **9:** 289; fig. 12.

♂. Head light reddish brown; first two antennal segments reddish-brown; rest grey-brown; antennae shaped much as in *americana;* ocellar warts as in *americana,* lighter than the rest of the head; thorax and abdomen brown, variegated; pronotal warts as in *americana;* legs pale. Fore wing: length, 3–5.5 mm.; width, 1.5–2.4 mm.; shape as in *americana;* membrane hyaline, with numerous grey maculations, sometimes diffuse, especially distally; costal space narrow; two cross-veins between R1 and Rs; MP3 + 4 not coalesced with Cu1; a series of five gradate veins present. Hind wing: length 2.4–3.5 mm.; width, 1.5–2.4 mm.; maculations as in the fore wing; no gradate series. Anal plates with a short but conspicuous tooth arising from the posterior margin at the top of the plates; a larger process arises from about the same part of the plate but is directed inwards; internal armature with the lateral processes somewhat longer than the inner pair, and the aedeagus nearly as long as the latter.

♀. Similar to the male in coloring; antennae pale yellow. Fore wing: length, 5.4 mm.; width, 2 mm.; slender; maculations and venation as in the male. Hind wing: length, 3.6 mm.; width, 1.8 mm.; maculations and venation as in the male.

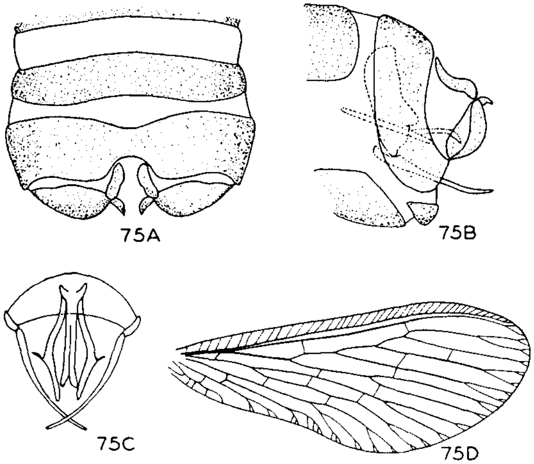

FIGURE 75. *Nallachius pulchellus* (Banks). A, terminal abdominal segments of male (holotype), dorsal view; B, same, lateral view; C, internal armature of male, ventral view; D, fore wing of female (allotype).

Types: two cotypes (♂, ♀) from woods near Soledad (Cienfuegos), Cuba, May 4, 1930 (P. J. Darlington, Jr.); in the Museum of Comparative Zoology.

A single male of this species is contained in the collection of the University of Kansas; it was taken in the Santa Rita Mountains, Arizona, 5000–8000 ft., July (F. H. Snow). At first glance I believed this to be a new species, but after comparing it with the types of *pulchellus,* I was unable to find any differences whatever, in genital or wing structure. It is somewhat larger than the types, but the Dilarids in general are very variable in size. There are several striking differences between this species and *americana;* e.g., the fore wings of the latter lack all cross-veins in the distal half of the wing, except the one between Rs and R1; whereas in *pulchellus,* there is a series of five gradates. The latter characteristic does not, in fact, fit Navas' original definition of Nallachius, which was described as lacking the gradates; but since *pulchellus* is not even remotely related to the other named genera, I prefer to modify the definition of Nallachius rather than establish a new genus.

The occurrence of this Dilarid in Arizona is of great interest, since the family has not previously been found anywhere in the Nearctic region except near the District of Columbia. That the species also occurs in the West Indies is likewise interesting, but Dr. Darlington tells me that he has observed many instances of close relationship between West Indian Coleoptera and those of northern Mexico and southern Arizona.

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PLATE 1

Fore wings of *Hemerobius* and *Sympherobius*

The photographs do not indicate relative sizes of the insects

Fig. 1, *Hemerobius humulinus* Linn. Fig. 2, *Hemerobius stigmaterus* Fitch. Fig. 3, *Hemerobius pacificus* Banks. Fig. 4, *Hemerobius bistrigatus* Currie. Fig. 5, *Hemerobius ovalis,* n. sp. Fig. 6, *Hemerobius simulans* Walker. Fig. 7, *Hemerobius dorsatus* Banks. Fig. 8, *Hemerobius costalis,* n. sp. Fig. 9, *Sympherobius barberi* Banks. Fig. 10, *Sympherobius occidentalis* (Fitch).

PLATE 2

Fore Wings of *Sympherobius, Megalomus,* and *Micromus*

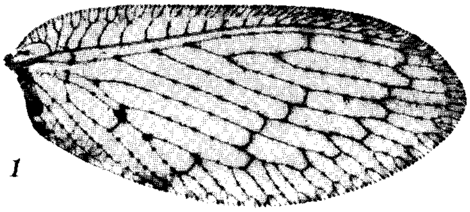
The photographs do not indicate relative sizes of the insects

Fig. 11, *Sympherobius killingtoni,* n. sp. Fig. 12, *Sympherobius californicus* Banks. Fig. 13, *Sympherobius pictus* (Banks). Lectotype. Fig. 14, *Sympherobius arizonicus* (Banks). Holotype. Fig. 15, *Sympherobius perparvus* (McLach.). Fig. 16, *Sympherobius angustus* Banks. Fig. 17, *Megalomus moestus* Banks. Fig. 18, *Megalomus angulatus,* n. sp. Holotype. Fig. 19, *Micromus angulatus* Steph. Fig. 20, *Micromus montanus* Hagen. Fig. 21, *Micromus variolosus* Hagen. Fig. 22, *Micromus subanticus* Walker.

PLATE 3

The photographs do not indicate relative sizes of the insects

Fig. 23, Fore wing of *Psectra diptera* (Burm.). Fig. 24, Fore wing of *Climacia areolaris* (Hagen). Fig. 25, Fore wing of *Lomamyia texana* Banks. Fig. 26, Fore wing of *Lomamyia flavicornis* (Walker). Fig. 27, Fore wing of *Polystoechotes punctatus* (Fabr.). Fig. 28, Fore and hind wing of *Platystoechotes lineatus,* n. sp.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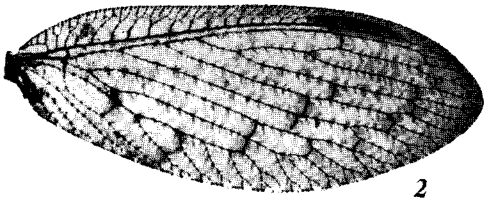
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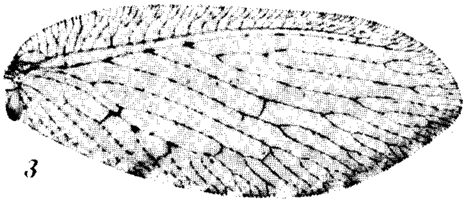
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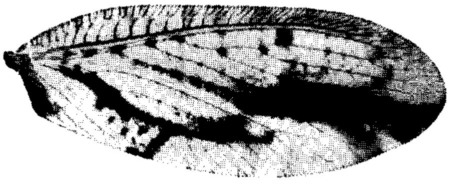
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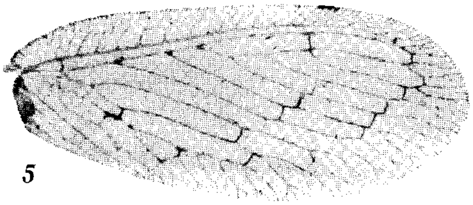
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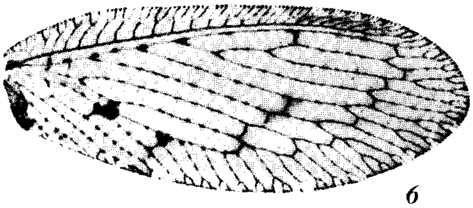
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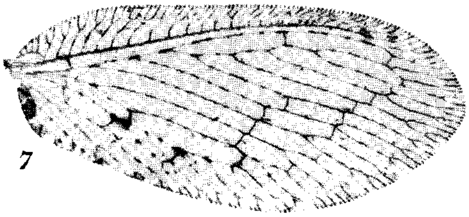
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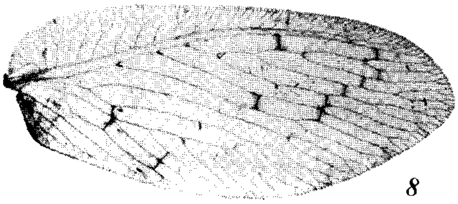
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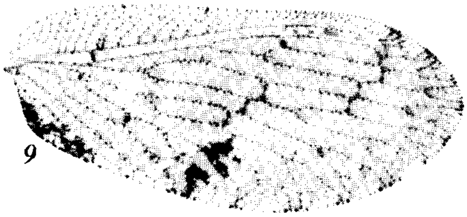
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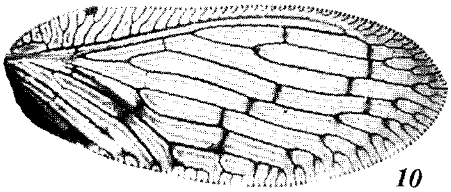
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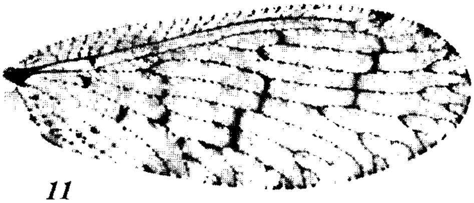

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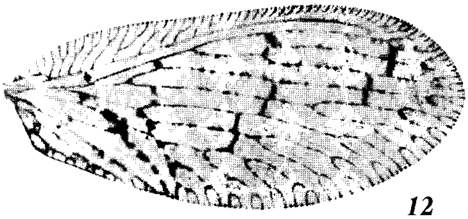

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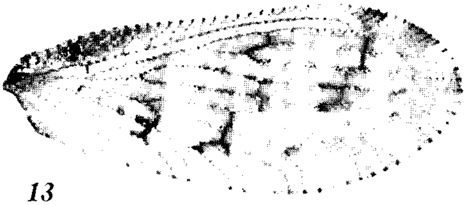

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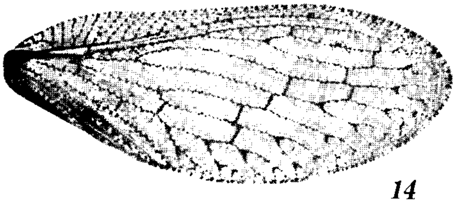

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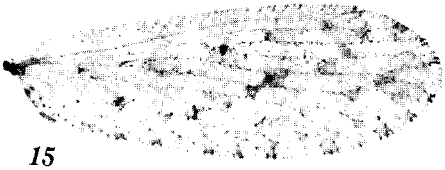

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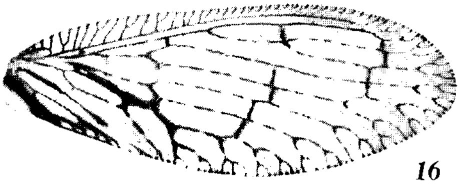

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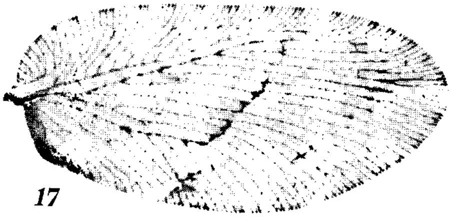

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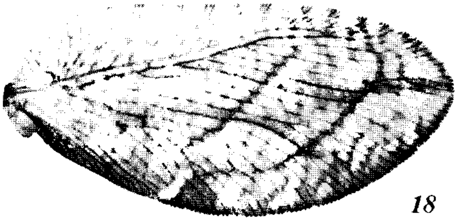

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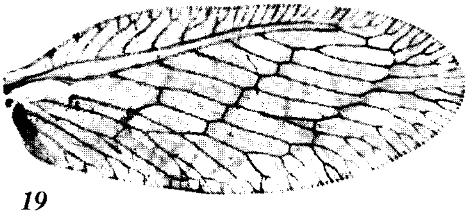

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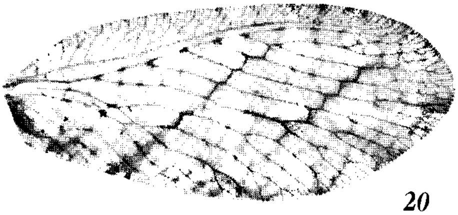

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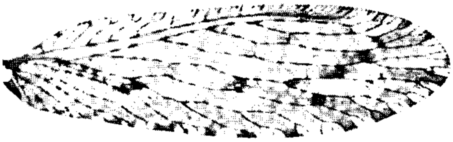

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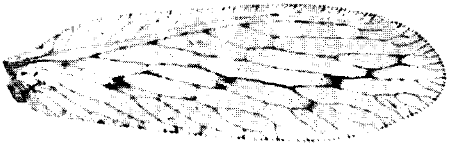

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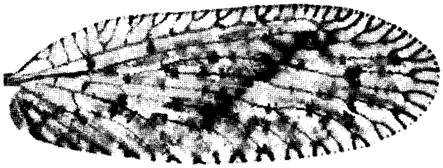

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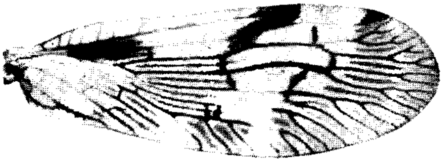

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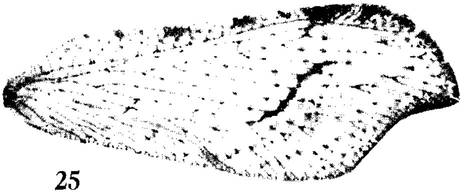

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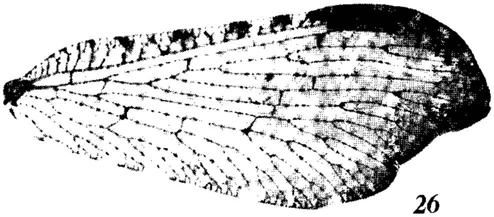

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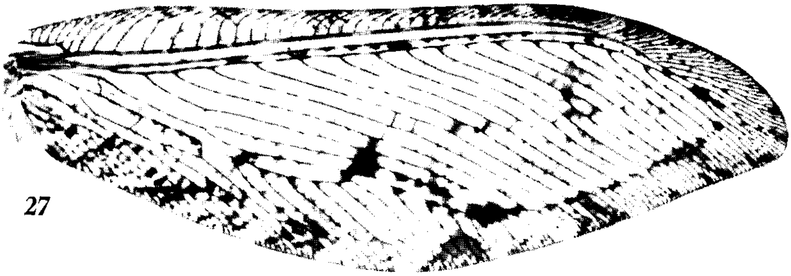

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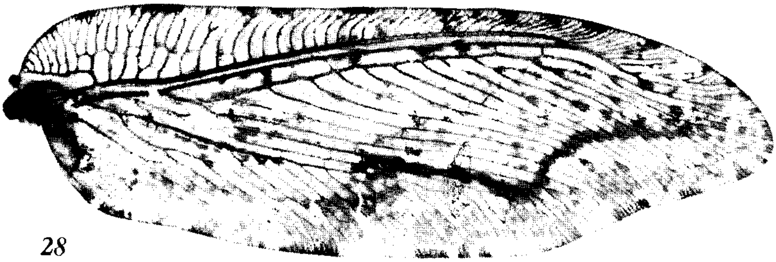

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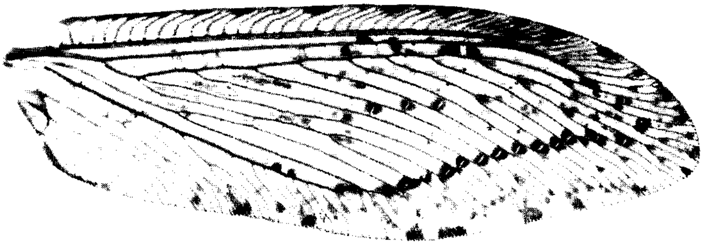

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PHOTOGRAPHIC EVIDENCE ON THE VISIBILITY OF COLOR PATTERNS IN BUTTERFLIES TO THE HUMAN AND INSECT EYE

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Aside from the plumage of birds, the most striking and conspicuous color patterns among animals are those found on the wings of butterflies. Some of these colors are due to pigments, others, particularly the metallic ones, are physical and the two types may occur in close combination.

We assume first that these color patterns are of recognition value to the butterflies themselves, and their development may have been influenced by sexual selection.

Furthermore they may represent something of a much more complicated nature. The independent discovery by Bates, Wallace and Trimen of remarkable resemblances in color pattern between various diverse butterflies made in the sixties of the past century is now well known to entomologists and biologists generally. The theories to explain these parallelisms on the basis of natural selection acting upon variations in palatable or mimicking species and tending to make these evolve into forms resembling unpalatable and "protected," but unrelated species, are equally common knowledge and have led to much controversy and a vast, detailed literature at the hands of later observers and theorists. Such disputation is still rife, and it must be admitted that no sane pronouncement may be made at the present time on the merits of the opposing views and I hold no brief for or against any of them. Nevertheless I am venturing to add a few notes on color vision among the insects themselves.

On account of certain inherent defects in human vision we see only a limited range of the spectrum and this does not coincide with the band that stimulates the eyes of certain other animals. Consequently we cannot hope to appreciate the color patterns of objects as seen for example by an insect without resorting to some subterfuge that enables us to shift our vision into the shorter wave lengths of light by blinding ourselves to the red and orange and at the same time penetrating into the invisible ultra-violet. Such possibilities are of course easily possible through certain simple photographic procedures. These were not available to the earlier students of mimicry, although they surmised that something might quite possibly be wrong with their interpretation of visual images in insect eyes.

Strangely enough, only scant attempts have been made in recent years to examine color patterns among butterflies by photography in light other than our own violet to red range of $\lambda 4000$-$\lambda 7600$. In 1933 Lutz published a number of photographs of butterflies registering the ultra-violet light reflected from their wings and gave an interesting account of the great change that takes place in the pattern of a number of species when thus illuminated, with our own entire range of vision excluded!

As nearly as has been ascertained the visual range of insects extends far into the ultra-violet, including wave lengths much shorter than those of sunlight after passage through the earth's atmosphere. Generally, however, it reaches only to about $\lambda 5900$ in the other direction and it is probable that the eye of most insects is not or only weakly receptive to colors which we see as orange and red. Such is undoubtedly the case with some types of insects and its extension to all is hardly open to much serious question, although we know that some species react slightly to orange and red and that they may confuse certain colors in the sense that they appear partially color blind. There is, of course, no close agreement between the numerous workers who have attempted to determine color sensitivity or perception among insects. As Lutz has clearly indicated (1933) the earlier experimenters failed to reckon with the ultra-violet, particularly in dealing with insects that visit flowers. Some other work has likewise been marred by failure to eliminate smell and memory. So far as the butterflies are concerned, Eltringham (1919) has brought much evidence forth to show that they distinguish colors fairly well except in the red region in the case of some species. Some of his conclusions however are not necessarily sound as he omits consideration of ultra-violet.

On the other hand so far as the terrestrial vertebrate enemies of insects are concerned it appears from the researches of Hess and others that their vision does not depart radically from that of the normal human being, consequently their relation to the phenomenon of mimicry is not affected by the matters specifically dealt with here.

Before proceeding to a discussion of our results, attention should be drawn to some other matters relating to color and mimicry. The simpler cases of mimicry among butterflies relate only to a single species serving as the model and another acting as the mimic and the similarity between the two is a coincidence of the color pattern, in form and shade in the two species without reference to any other related or unrelated species. In the case of Müllerian mimicry as first noted by Fritz Müller where numerous individual examples of mimicry in a region occur together, involving a series of related models and a series of mimics, there is a marked tendency toward the appearance of certain similar color patterns among several pairs of species. Moreover, this type commonly involves yellow, orange and red patterns to which insects are apparently only slightly sensitive.

In the photographs which form the basis for the present contribution I have attempted to reproduce in monotone the visual image that each butterfly should produce in the eye of another butterfly or other insect. It is freely admitted that one makes a bold assumption to believe that these are close to accuracy, but they represent an approach in this direction and have revealed a possible discrimination of tone and brilliancy that were not anticipated at the outset of the experiment.

The butterflies selected are mainly the species illustrated in Punnett's "Mimicry in Butterflies" (1915) which include many of the more striking and better known cases that have been noted. This material was available in the large Week's collection of the Museum of Comparative Zoology, and I am very grateful for the opportunity to make use of the specimens from this collection for the present purpose.

All the photographs were made with a Leica camera fitted with focussing attachment, the exposures determined by trial and error. Those for ultra-violet light are short, but satisfactory exposures for fluorescence required, with our apparatus, about ten minutes each. Although the methods used are simple, much time is required for the necessary manipulations as well as the processing of the black and white negatives and positives. For a considerable part of this tedious work I am indebted to Mrs. A. S. O'Connor who aided me throughout the several operations.

Four photographs were made of each butterfly. A natural color transparency on Kodachrome film gives a very accurate picture of the color pattern as seen by the human eye. These exposures were made on Kodachrome A film illuminated by a pair of flood-light bulbs. For the three other photographs which are in monotone, a quartz mercury vapor lamp ("Uviare") was used as the source of illumination, enclosed in a light-tight box provided with a window.[1] For two of the others this window was covered by a filter (Wratten No. 18) that transmits ultra-violet only, absorbing all the visible spectrum. Thus illuminated (Fig. 1, A) it is possible without further filters to secure a photograph of the ultra-violet as reflected by the wings, using an orthochromatic film that serves to eliminate a very slight amount of red that passes through the No. 18 filter.

Since there is much variation in the transparency of different photographic lenses to ultra-violet light, it is important to know the spectral limit passed by any particular lens before attempting to interpret photographs made with it. I am deeply indebted to Professor Theodore Lyman of Harvard University who had such determinations made for me in his laboratory. The Leitz "Elmar" lens was found to pass the band at λ3131 and also, of course the one near λ3650. On this account it was deemed suitable for our present purpose.

It is not possible to reproduce the color photographs here and the reader who may not be familiar with the species dealt with is referred to Punnett's book ('15) in which the colors are shown with close fidelity.

Some of the pigments on the wings fluoresce when illuminated by ultra-violet light and this pattern is visible to the human eye without any further filter since the fluorescent light is within our visual range. It varies greatly in different forms as might be expected, since there is a wide range in both color and intensity among all sorts

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[1] Viewed directly in this light, without any filter, the colors and patterns of the butterflies appear to our own eyes essentially as they do in daylight.

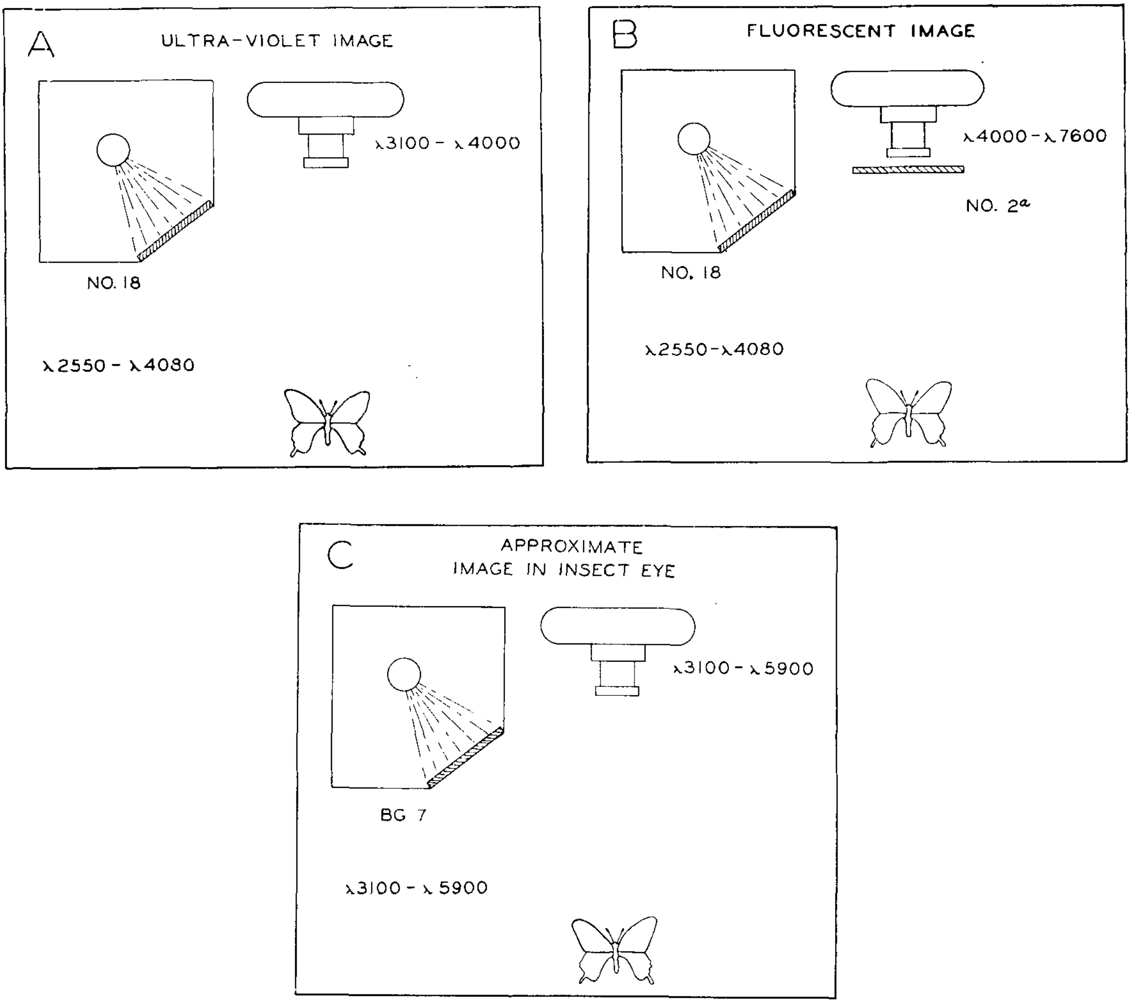

Fig. 1. Arrangement of light, filters and camera used in securing the photographs shown and described in the present paper. A, ultra-violet image; B, fluorescent image; C, approximate image in insect eye.

of organic and inorganic substances. This fluorescence can be easily photographed by placing a second yellow filter (Wratten 2a) between the object and the camera (Fig. 1, B) to absorb the reflected ultra-violet and pass only the visible wave length (λ4000–λ7600) using a panchromatic emulsion for the record. This light is much weaker and requires a far longer exposure than that needed to register the more powerful ultra-violet reflection which must of course be entirely excluded in order that it may not obscure the weaker fluorescence. This fluorescent image is of interest mainly as a comparison between different pigments as it does not enter into the visual picture of any animals under natural conditions.[1]

The fourth photograph is of the greatest interest from the standpoint of insect vision. It is obtained by using the ultra-violet lamp with the No. 18 filter replaced by a blue filter (Jena BG7) in the window of the lamp housing. This illuminates the butterfly with light that includes some ultra-violet but lacks orange and red, a range approximately from λ3300–λ5900 (Fig. 1, C). This is intended to approximate rather closely the visual image in the insect's eye since it includes the photographically very strong ultra-violet band at λ3650. Some of the daylight waves of shorter lengths are excluded by the filter glass and optical lenses since the effective lower limit of these is approximately from λ3200–λ3500. As strong invisible light is present, this photographic record can be made only in monochrome since ultra-violet registers as blue in "natural color" transparencies. The use of Kodachrome for this would presumably falsify the image as seen by the insect although we have really not the slightest hint as to what "color" or other impression may result from its proven sensitivity to ultra-violet light. This image may, of course be similar to blue, but there would seem to be absolutely no hope of securing other than metaphysical proof or denial of this.

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[1] Cockayne ('24) has examined a great many butterflies and moths under ultra-violet illumination and recorded the fluorescence observed.

If we compare the full color transparencies with those made by reflected ultra-violet light, it is at once evident that the patterns are usually changed but to a varying degree that could not be predicted by visual examination. To take, for example, the butterfly and moth, *Papilio laglazei* and *Alcides cydnus* the remarkable similarity of pattern is repeated in ultra-violet, but the moth is only slightly fluorescent. Again, in *Planema aganice* and its supposed mimic *Pseudacraea imitator* the ultra-violet reflection of both butterflies is very similar. Generally in patterns where orange and red predominate, the ultra-violet reflection is reduced, but not so strongly as might be expected, *e. g.*, *Danais plexippus*, but fluorescence is reduced to almost nothing.

In four quite similar but not related species, *Papilio philenor, P. troilus, Argynnis diana* ♀ and *Limenitis astyanax* there are considerable differences in ultra-violet, but much greater ones in fluorescence.

If we examine a dark, brownish-red species like *Danais gilippa berenice* it is seen that there is a strong ultra-violet reflection from the white spots, a weaker, but pronounced one from the red areas and fluorescence is confined to the white spots where it is very brilliant. The photograph including ultra-violet but eliminating orange and red (λ3300–λ5900) has highly corrected color values as judged by the human eye. This is obviously due to the fact that the considerable amount of ultra-violet reflected from the red, combined with some reflection of blue and green compensates for the red and produces an illumination and pattern closely approximating our own impression of this butterfly. That is not an isolated case is shown by similar photographs of *Danais archippus* (Plate 1, figs. 1, 2) (= *Anosia plexippus*). In this species the combination light of λ3300–λ5900 again gives an image well corrected for the human eye. Moreover, in a supposed mimic, *Limenitis archippus*, the same color correction is obtained by these wave lengths (Plate 1, figs. 3, 4) and this correction extends also to a much darker, related butterfly, *Limenitis floridensis* where the red-orange is exceedingly dark (Plate 1, figs. 5, 6).

In other examples of red-orange color the same color relations prevail, as shown by *Danais chrysippus*, var. *alcippus* (Plate 1, figs. 7, 8) and *Hypolimnas dorypppoides*. These two are also forms regarded as model and mimic respectively.

Another series of models and mimics are represented by heliconiid butterflies and ithomiines of very similar colors and patterns. One or two of these will suffice for our purpose. In *Heliconius eucrate* (Plate 2, figs. 13, 14) and *Mechanites lysimnia* (Plate 2, figs. 15, 16) there is a rather close correspondence of the color pattern in all photographs of each as the pattern is well reproduced, except that the λ3300–λ5900 band gives good differentiation of the orange, which is less clearly marked in the ultra-violet illumination. In *Heliconius eucoma* var. *pardalinus* and *Mechanites agaensis* there is an exception to the general rule as the very deep orange is poorly indicated and the λ3300–λ5900 illumination does not give good differentiation in either species, although the two are essentially similar to one another. In another pair of similarly patterned species, *Heliconius telesiphe* (Plate 2, figs. 9, 10) and a nymphalid, *Colaenis telesiphe* (Plate 2, figs. 11, 12) both the ultra-violet and λ3300–λ5900 range serve to reproduce the pattern very accurately. Comparing *Heliconius melpomene* and the similarly patterned pierid butterfly, *Perrute charops* (Plate 2, figs. 17, 18) it is seen that the λ3300–λ5900 range gives a close similarity, although the ultra-violet alone does not.

As might be expected, species where red or orange do not enter into the pattern the ultra-violet alone gives a closer approximation to the human image than is usually the case where these colors are present. This is seen in two pairs of species, *Amauris niavius* and *Amauris echeria* which are danaines and two varieties of the polymorphic *P. dardanus* (var. *hippocoön* and var. *cenea*). Aside from an excessive reflection from the white and yellow markings, the ultra-violet illumination is a fairly good replica of the human image.

In conclusion it may be repeated that the visual picture of butterflies produced in the human eye differs in varying degrees from photographs made by reflected ultra-violet light. A range of λ3300–λ5900 which includes some ultra-violet that is photographically very active (λ3650) appears to approach the human image very closely, and theoretically at least should represent the image in the insect eye. It follows that certain red and orange markings are readily visible to insects on account of the ultra-violet that they reflect and not by reason of the reflected orange or red which affects our own eyes.

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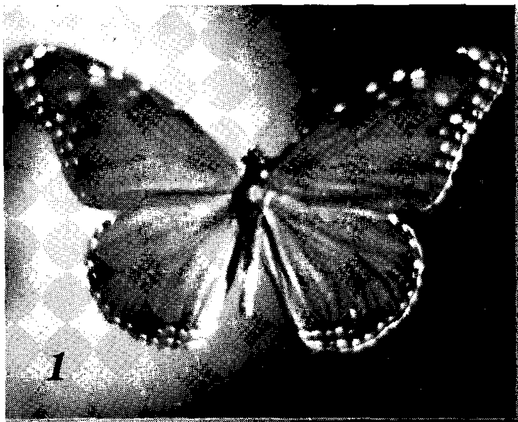
EXPLANATION OF PLATES

PLATE 1

1. *Danais archippus*, ultra-violet reflection.
2. *Danais archippus*, approximate image in insect eye.
3. *Limenitis archippus*, ultra-violet reflection.
4. *Limenitis archippus*, approximate image in insect eye.
5. *Limenitis floridensis*, ultra-violet reflection.
6. *Limenitis floridensis*, approximate image in insect eye.
7. *Danais chrysippus*, ultra-violet reflection.
8. *Danais chrysippus*, approximate image in insect eye.

PLATE 2

9. *Heliconius telesiphe*, ultra-violet reflection.
10. *Heliconius telesiphe*, approximate image in insect eye.
11. *Colaenis telesiphe*, ultra-violet reflection.
12. *Colaenis telesiphe*, approximate image in insect eye.
13. *Heleconius eucrate*, ultra-violet reflection.
14. *Heliconius eucrate*, approximate image in insect eye.
15. *Mechanites lysimnia*, ultra-violet reflection.
16. *Mechanites lysimnia*, approximate image in insect eye.
17. *Pereute charops*, ultra-violet reflection.
18. *Pereute charops*, approximate image in insect eye.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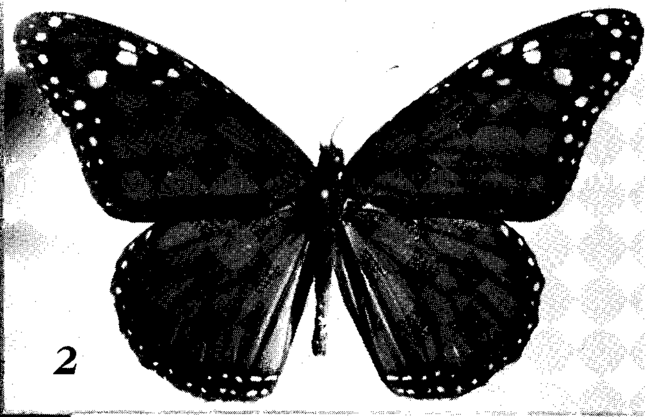
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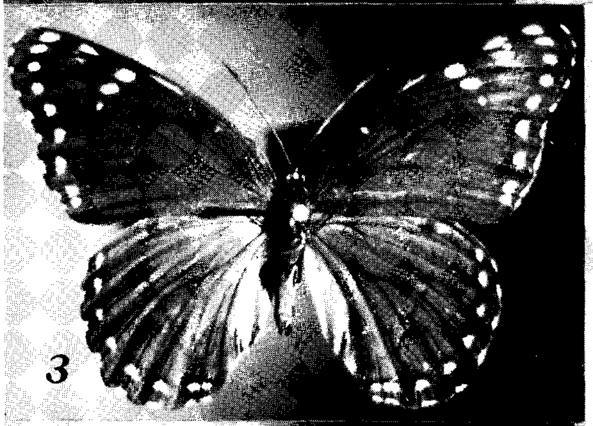
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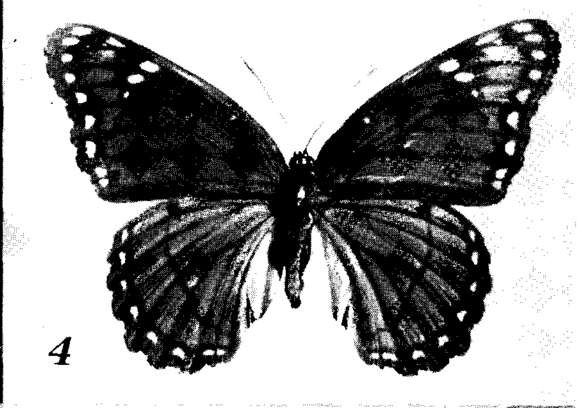
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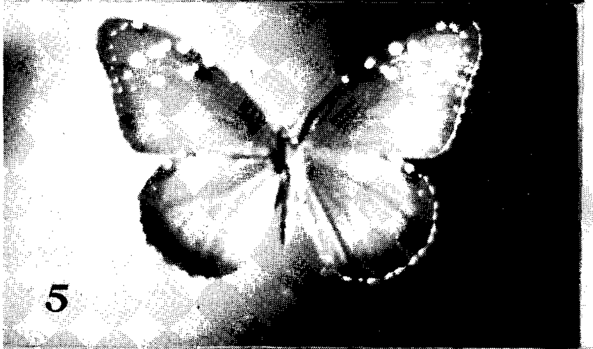
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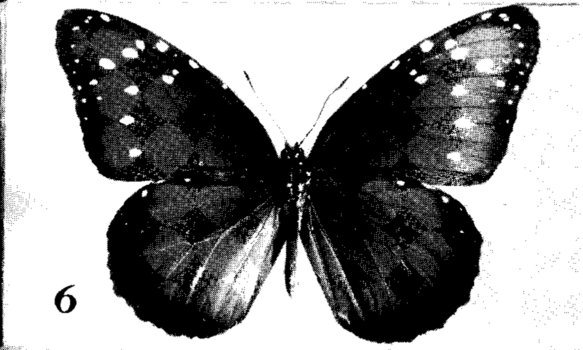
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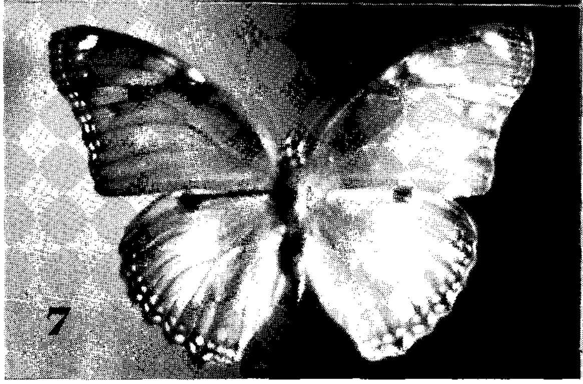
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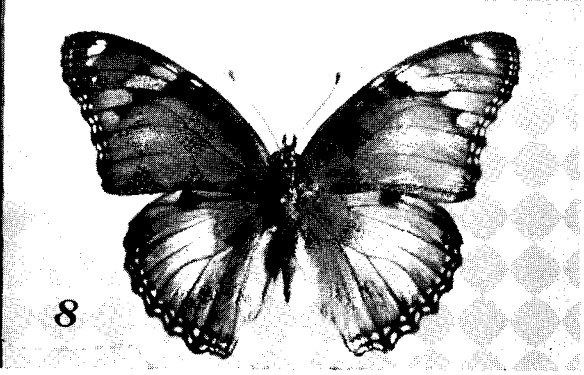
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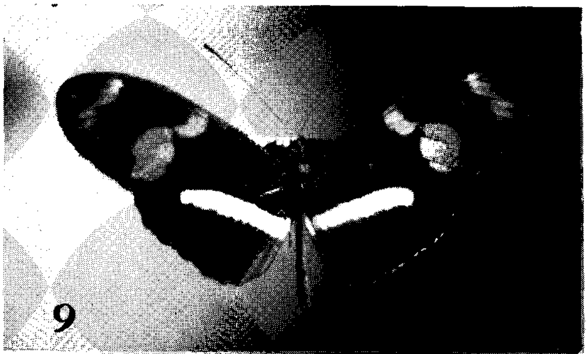

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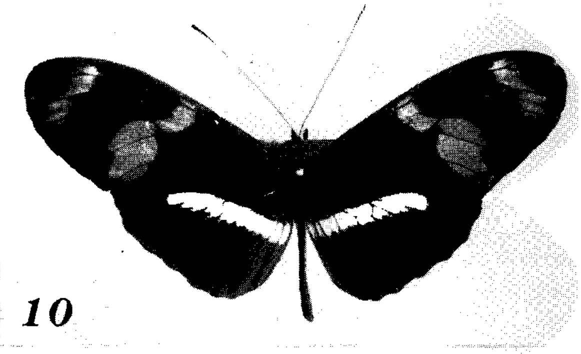

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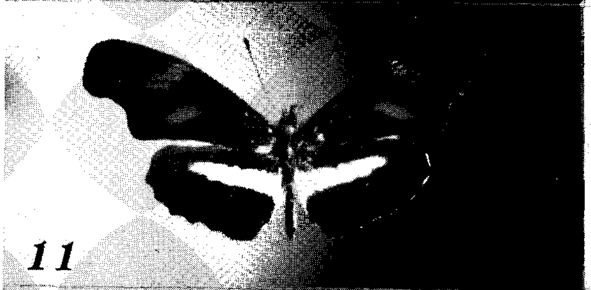

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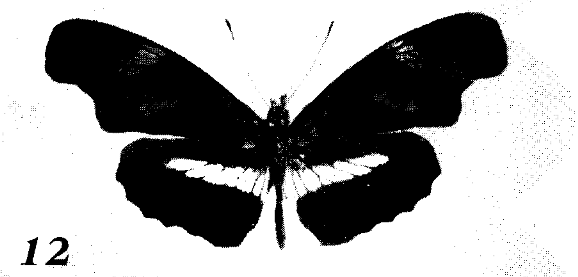

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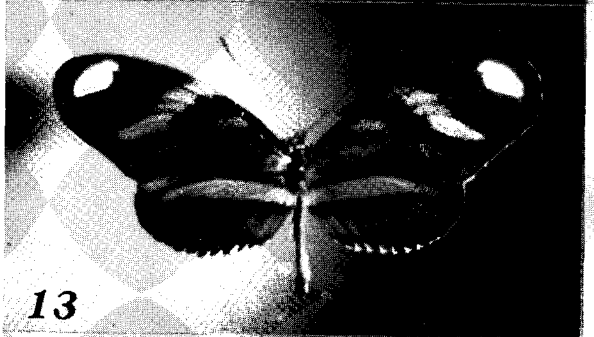

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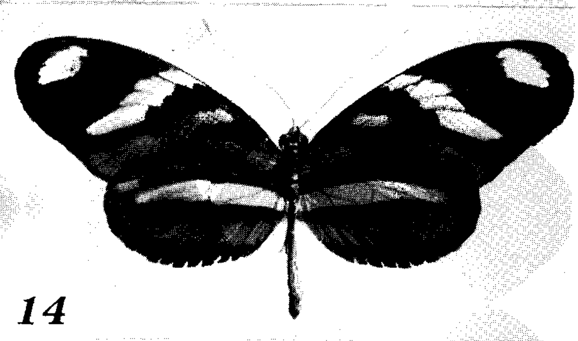

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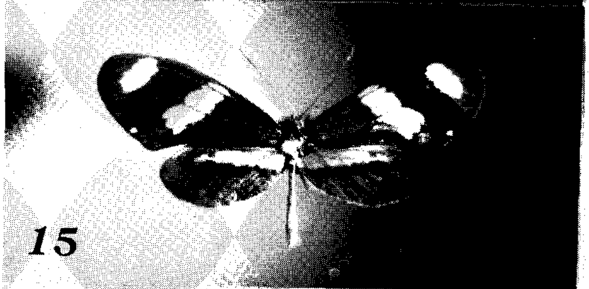

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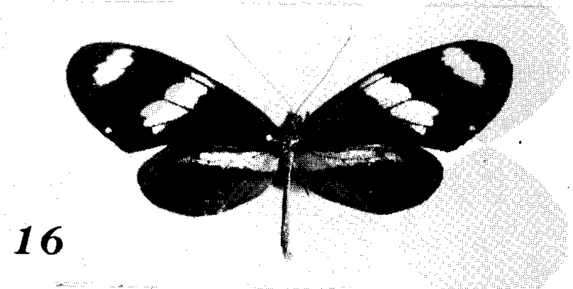

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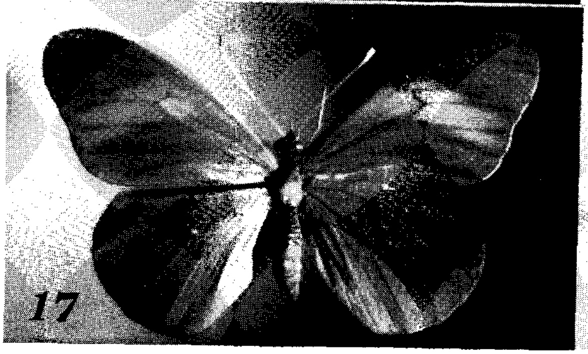

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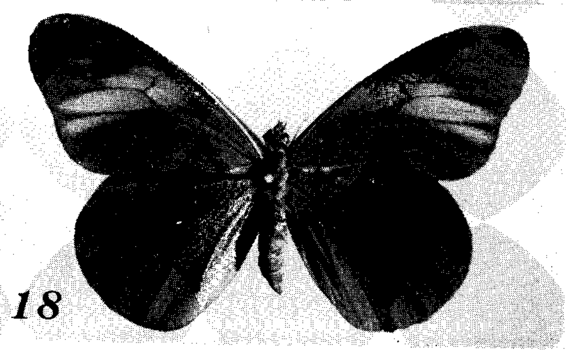

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THE APPROXIMATE SOLUTION OF SINGULAR INTEGRAL EQUATIONS ARISING IN ENGINEERING PRACTICE

By Francis B. Hildebrand

THE APPROXIMATE SOLUTION OF SINGULAR INTEGRAL EQUATIONS ARISING IN ENGINEERING PRACTICE

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1. *Introduction.* In a recent paper[1] Crout has given a method of solution of integral equations by polynomial approximation. The purpose of the present paper is to extend this method to the solution of certain integral equations which arise in a natural way in the formulation of problems of static field theory, air-foil theory, elasticity, heat and fluid flow, diffusion, etc., wherein the unknown function, as well as the kernel or Green's function, may have infinite singularities of known order.

Several specific problems of this type are solved numerically, the problems being chosen, for the most part, so that the exact solutions are known, and the results are shown to be well within engineering limits of accuracy. Use is made of a method of least squares which is given in a paper[2] now in publication, and somewhat extended in the present paper.

2. *Outline of the General Method.* We consider here the solution of integral equations of the first kind, of the form

$$\varphi(x) = \int_a^b \sigma(\xi) G(x, \xi) d\xi \tag{2.1}$$

where φ and G are given, and suppose that $\sigma(x)$ is known, from physical considerations or otherwise, to have singularities of known order at certain points in the interval (a, b). Constructing $s(x)$, a linear combination of r suitable functions $s_j(x)$, possessing the correct singularities at these points,

$$s(x) = \sum_{j=1}^{r} \chi_j s_j(x),$$

where the χ's are constants to be determined, we set

$$\sigma(x) \approx \bar{\sigma}(x) = s(x) + y(x), \tag{2.2}$$

where $y(x)$ is a polynomial of degree $2n$, specified by its ordinates at $2n + 1$ points equally spaced over the interval (a, b).

If the spacing is h and the corresponding values of $y(x)$ are denoted by $y_{-n}, y_{-n+1}, \ldots, y_0, \ldots, y_{n-1}, y_n$, and if we set $x = (a+b)/2 + \lambda h$, the polynomial can be expressed conveniently in the Lagrangean form

$$y(x) = \sum_{i=-n}^{n} K_i(\lambda) y_i, \tag{2.3}$$

where $K_i(\lambda)$ is a polynomial of degree $2n$ in λ,

$$K_i(\lambda) = \sum_{s=0}^{2n} B_{si} \lambda^s. \tag{2.4}$$

Tabulated values of the K's for $-n \leqslant \lambda \leqslant n$ by tenths, $n = 1, 2, 3$, as well as tables of the coefficients B_{si}, are given in Crout's paper.[1]

Now $\bar{\sigma}(x)$ is specified by $2n + r + 1$ independent parameters. Substituting $\bar{\sigma}(x)$ for $\sigma(x)$ in the right hand side of (2.1) and assuming that $\bar{\sigma}(x)$ approximates $\sigma(x)$ satisfactorily, it follows that

$$\varphi(x) \approx \sum_{j=1}^{r} \chi_j \int_a^b s_j(\xi) G(x,\xi) d\xi + \sum_{i=-n}^{n} y_i \int_a^b K_i(\lambda)\, G(x,\xi) d\xi. \tag{2.5}$$

The parameters can now be determined by any set of conditions leading to a set of $2n + r + 1$ independent linear equations. Suppose that we require the integral of the square of the difference between the two sides of (2.5) to be a minimum.[2] If we write (2.5) in the form

$$\varphi(x) \approx \sum_{j=1}^{r} \chi_j S_j(x) + \sum_{i=-n}^{n} y_i Y_i(x), \tag{2.5'}$$

the χ's and y's are to be determined so that

$$\int_a^b \left[\sum_{j=1}^{r} \chi_j S_j(x) + \sum_{i=-n}^{n} y_i Y_i(x) - \varphi(x) \right]^2 dx = \text{min.} \tag{2.6}$$

Equating the partial derivatives to zero, we obtain the system of linear equations

$$\begin{aligned} \sum_{j=1}^{r} \chi_j \int_a^b S_j(x) S_p(x) dx + \sum_{i=-n}^{n} y_i \int_a^b Y_i(x) S_p(x) dx &= \int_a^b \varphi(x) S_p(x) dx, \quad p = 1, 2, \ldots, r; \\ \sum_{j=1}^{r} \chi_j \int_a^b S_j(x) Y_q(x) dx + \sum_{i=-n}^{n} y_i \int_a^b Y_i(x) Y_q(x) dx &= \int_a^b \varphi(x) Y_q(x) dx, \quad q = -n, \ldots, n. \end{aligned} \tag{2.7}$$

In general, direct integration would be impractical. However, if we employ approximate integration with weighting coefficients D_k, this system of equations takes the form

$$
\begin{aligned}
&\sum_{j=1}^{r} \chi_j \sum_{k=1}^{m} D_k S_j(x_k) S_p(x_k) + \sum_{i=-n}^{n} y_i \sum_{k=1}^{m} D_k Y_i(x_k) S_p(x_k) \\
&\qquad = \sum_{k=1}^{m} D_k \varphi(x_k) S_p(x_k), \ p = 1, 2, \ . \ . \ ., r; \\
(2.8)\quad &\sum_{j=1}^{r} \chi_j \sum_{k=1}^{m} D_k S_j(x_k) Y_q(x_k) + \sum_{i=-n}^{n} y_i \sum_{k=1}^{m} D_k Y_i(x_k) Y_q(x_k) \\
&\qquad = \sum_{k=1}^{m} D_k \varphi(x_k) Y_q(x_k), \ q = -n, \ . \ . \ ., n.
\end{aligned}
$$

It is now easy to verify the fact that *the augmented matrix of equations* (2.8) *can be obtained by multiplying the augmented matrix of the system*

$$
(2.9)\quad \varphi(x_k) \approx \sum_{j=1}^{r} \chi_j S_j(x_k) + \sum_{i=-n}^{n} y_i Y_i(x_k), \qquad k = 1, 2, \ . \ . \ ., m,
$$

by the matrix formed by multiplying the kth column of the transposed coefficient matrix by the integration coefficient D_k. For, if we denote $S_j(x_k)$ by S_j^k and $Y_j(x_k)$ by Y_j^k, this matrix product takes the form

$$
\left\| \begin{array}{llll}
D_1S_1^1 & D_2S_1^2 & \ldots\ldots & D_mS_1^m \\
D_1S_2^1 & D_2S_2^2 & \ldots\ldots & D_mS_2^m \\
\ldots & \ldots & \ldots & \ldots \\
D_1S_r^1 & D_2S_r^2 & \ldots\ldots & D_mS_r^m \\
D_1Y_{-n}^1 & D_2Y_{-n}^2 & \ldots\ldots & D_mY_{-n}^m \\
\ldots & \ldots & \ldots & \ldots \\
D_1Y_n^1 & D_2Y_n^2 & \ldots\ldots & D_mY_n^m
\end{array} \right\|
\cdot
\left\| \begin{array}{lllllll}
S_1^1 & S_2^1 & \ldots\ldots & S_r^1 & Y_{-n}^1 & \ldots\ldots & Y_n^1 \quad \varphi^1 \\
S_1^2 & S_2^2 & \ldots\ldots & S_r^2 & Y_{-n}^2 & \ldots\ldots & Y_n^2 \quad \varphi^2 \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
S_1^m & S_2^m & \ldots\ldots & S_r^m & Y_{-n}^m & \ldots\ldots & Y_n^m \quad \varphi^m
\end{array} \right\| =
$$

and, multiplying according to the row-times-column convention of matrix multiplication, the product matrix,

$$
\left\| \begin{array}{lllllll}
\sum D_kS_1^kS_1^k & \ldots\ldots & \sum D_kS_r^kS_1^k & \sum D_kY_{-n}^kS_1^k & \ldots\ldots & \sum D_kY_n^kS_1^k & \sum D_k\varphi^kS_1^k \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
\sum D_kS_1^kS_r^k & \ldots\ldots & \sum D_kS_r^kS_r^k & \sum D_kY_{-n}^kS_r^k & \ldots\ldots & \sum D_kY_n^kS_r^k & \sum D_k\varphi^kS_r^k \\
\sum D_kS_1^kY_{-n}^k & \ldots\ldots & \sum D_kS_r^kY_{-n}^k & \sum D_kY_{-n}^kY_{-n}^k & \ldots\ldots & \sum D_kY_n^kY_{-n}^k & \sum D_k\varphi^kY_{-n}^k \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
\sum D_kS_1^kY_n^k & \ldots\ldots & \sum D_kS_r^kY_n^k & \sum D_kY_{-n}^kY_n^k & \ldots\ldots & \sum D_kY_n^kY_n^k & \sum D_k\varphi^kY_n^k
\end{array} \right\|,
$$

where $\sum$ has been written for $\sum_{k=1}^{m}$, is seen to be the augmented matrix of equations (2.8).

It is also clear that in place of the coefficients D_k it is permissible to use as weighting coefficients the numbers $D_k' = \mu D_k$, where μ is chosen conveniently. This gives a practical method of obtaining $2n + r + 1$ linear equations to determine the parameters specifying the approximate solution $\bar{\sigma}(x)$. In each case a rough check on the error can be had by substituting the calculated values of the parameters in equations (2.9).

The examples which follow will illustrate the fact that the coefficients of (2.9) can be obtained conveniently and systematically by the use of matrix multiplication, wherein certain matrices depend only upon the particular kernel involved, while others which depend only upon certain general characteristics of the problem can be computed once and used repeatedly in a variety of problems of a similar type.

3. *Applications.* To illustrate the procedure we first set the following problem:

Problem 1. A long, uncharged, perfectly conducting strip of breadth 2a is placed in a two-dimensional electrostatic field (a field which does not vary in the direction of the length of the strip). *Find the distribution of the induced charge.* We consider a unit length of the strip and field and denote by $\sigma(x)$ the required charge density, x being measured from one edge of the strip along a perpendicular to the edge. Then, choosing the line $x = a$, at the center of the strip, to be the locus of zero potential, the potential at a distance x from the edge $x = 0$, due to a charge distribution $\sigma(x)$ is given by

$$
-2 \int_0^{2a} \sigma(\xi) \log \left| \frac{\xi - x}{\xi - a} \right| d\xi.
$$

If we denote the potential at x due to the external field by $-\varphi(x)$, again taking the line $x = a$ to be the reference locus, so that $\varphi(a) = 0$, and if we assume that the presence of the strip has a negligible effect upon the distribution of charges producing the external field, then the condition that the strip be an equipotential surface is given by the equation

$$(3.1) \qquad \varphi(x) = -2\int_0^{2a} \sigma(\xi)\log\left|\frac{\xi-x}{\xi-a}\right| d\xi.$$

Since $\varphi(x)$ is known, this is an integral equation of the first kind for determining $\sigma(x)$.

It is well known that at a non-reentrant corner of angle opening θ the charge distribution on a conductor has a singularity of order $(1 - \pi/\theta)$. In particular, for a strip of finite breadth we have $\theta = 2\pi$ at the edges so that the singularities at the edges are of order $\frac{1}{2}$; that is, $\sigma(x) \sim Ax^{-\frac{1}{2}}$ near $x = 0$, and $\sigma(x) \sim B(2a-x)^{-\frac{1}{2}}$ near $x = 2a$, where A and B are constants.

It is convenient to solve Problem 1 for two special types of fields and to obtain the general solution by superposition.

a. *Suppose that the external field is antisymmetrical with respect to a plane perpendicular to the strip at its center line.* Then $\varphi(x) = -\varphi(2a - x)$. Here we set $s(x) = \chi\left\{\left(\frac{x}{a}\right)^{-\frac{1}{2}} - \left(2 - \frac{x}{a}\right)^{-\frac{1}{2}}\right\}$ where χ is an arbitrary parameter, and approximate $\sigma(x)$ by the combination of $s(x)$ and a fourth degree polynomial specified by its values $y_2, y_1, y_0, -y_1$, and $-y_2$ at the points $x = 0$, $a/2$, a, $3a/2$, and 2a, respectively. Since $\sigma(x)$ is continuous at $x = a$, it follows that $y_0 = 0$, and the polynomial can be expressed in the Lagrangean form

$$y(x) = \sum_{i=-2}^{2} K_i(\lambda)y_i = \sum_{i=1}^{2} \bar{K}_i(\lambda)y_i,$$

where $\lambda = 2(x/a - 1)$ and $\bar{K}_i(\lambda) = K_{-i}(\lambda) - K_i(\lambda)$. Assuming that $\sigma(x)$ is approximated satisfactorily by $\bar{\sigma}(x) = s(x) + y(x)$, it follows from (3.1) that

$$(3.2) \quad \varphi(x) \approx -2\int_0^{2a} \{s(\xi) + y(\xi)\}\log\left|\frac{\xi-x}{\xi-a}\right| d\xi.$$

We next set

$$(3.3) \qquad \varphi_P(x) = -2\int_0^{2a} y(\xi)\log\left|\frac{\xi-x}{\xi-a}\right| d\xi$$

and

$$(3.4) \qquad \varphi_S(x) = -2\int_0^{2a} s(\xi)\log\left|\frac{\xi-x}{\xi-a}\right| d\xi,$$

and require that

$$(3.5) \quad \varphi(x_k) \approx \varphi_P(x_k) + \varphi_S(x_k),\ k = 1, \ldots, 5,$$

corresponding to equations (2.9) of the preceding section, where the points x_k are given by $x = 0$, $a/8$, $a/4$, $a/2$, and $3a/4$, respectively. Then also, because of the antisymmetry, (3.2) is true for the corresponding points in the interval $(a, 2a)$ and at $x = a$.

From (3.3) we have

$$(3.6) \quad \varphi_P(x_k) = -2\sum_{i=1}^{2} y_i \int_0^{2a} \bar{K}_i(\lambda)\log\left|\frac{\xi-x_k}{\xi-a}\right| d\xi.$$

If we set

$$\bar{K}_i(\lambda) = \sum_{s=0}^{4} c_{si}\left(\frac{\xi}{h}\right)^s$$

and notice that $h = a/2$, the coefficient of y_i in the kth equation of (3.6) becomes

$$-2\sum_{s=0}^{4} 2^s a^{-s} c_{si}\int_0^{2a} \xi^s \log\left|\frac{\xi-x_k}{\xi-a}\right| d\xi,$$

so that the matrix of coefficients of the y's in (3.6) is given by the matrix product

$$-2\left\| 2^s a^{-s}\int_0^{2a} \xi^s \log\left|\frac{\xi-x_k}{\xi-a}\right| d\xi\right\| \cdot \left\| c_{si} \right\|,$$

where the row and column indices are k and s in the first matrix and s and i in the second, respectively.

The coefficients c_{si} are found by first placing $\lambda = 2(\xi/a - 1) = \xi/h - 2$ in (2.4), so that

$$K_i(\lambda) = \sum_{s=0}^{4} B_{si}(\xi/h - 2)^s,$$

the values of the B's being taken from Crout's tables.[1] Then, placing $\bar{K}_i(\lambda) = K_{-i}(\lambda) - K_i(\lambda)$, the coefficient c_{si} is read directly as the coefficient of $(\xi/h)^s$ in the expression for $\bar{K}_i(\lambda)$.

Carrying out the integrations directly, the required matrix is given by the product[3,4]

$$-2a\left\|\begin{matrix} 1.38629 & 4.77259 & 12.72690 & 35.51404 & 105.11160 \\ .91871 & 4.22212 & 11.65644 & 32.71051 & 96.75405 \\ .63275 & 3.61684 & 10.42869 & 29.58000 & 87.57357 \\ .26162 & 2.34721 & 7.47519 & 22.00422 & 65.80978 \\ .06317 & 1.10524 & 3.92619 & 12.21317 & 37.47033 \end{matrix}\right\| \cdot \frac{1}{6}\left\|\begin{matrix} 6 & 0 \\ -11 & 16 \\ 6 & -12 \\ -1 & 2 \\ 0 & 0 \end{matrix}\right\| = a\left\|\begin{matrix} 1.11111 & 1.77778 \\ 1.23431 & 2.30078 \\ .99886 & 2.70495 \\ .46753 & 2.71285 \\ .14486 & 1.66806 \end{matrix}\right\|$$

Hence, writing φ_{Pk} for $\varphi_P(x_k)$, equations (3.6) have been obtained in the form

$$\begin{aligned} \varphi_{P1} &= 1.11111\, ay_2 + 1.77778\, ay_1, \\ \varphi_{P2} &= 1.23431\, ay_2 + 2.30078\, ay_1, \\ \varphi_{P3} &= .99886\, ay_2 + 2.70495\, ay_1, \\ \varphi_{P4} &= .46753\, ay_2 + 2.71285\, ay_1, \\ \varphi_{P5} &= .14486\, ay_2 + 1.66806\, ay_1. \end{aligned} \tag{3.7}$$

Next, computing

$$\varphi_S(x_k) = -2\chi \int_0^{2a} \left\{ \left(\frac{\xi}{a}\right)^{-\frac{1}{2}} - \left(2 - \frac{\xi}{a}\right)^{-\frac{1}{2}} \right\} \log\left|\frac{\xi - x_k}{\xi - a}\right| d\xi$$

directly, we obtain

$$\begin{aligned} &\varphi_{S1} = 7.84207\, \chi a, \quad \varphi_{S2} = 6.56236\, \chi a, \\ &\varphi_{S3} = 5.50583\, \chi a, \quad \varphi_{S4} = 3.58146\, \chi a, \\ &\varphi_{S5} = 1.76929\, \chi a, \end{aligned} \tag{3.8}$$

where $\varphi_{Sk} = \varphi_S(x_k)$.

Combining (3.7) and (3.8), we have determined equations (3.5) in the form

$$\begin{aligned} \varphi_1 &\approx 1.11111\, ay_2 + 1.77778\, ay_1 + 7.84207\, a\chi, \\ \varphi_2 &\approx 1.23431\, ay_2 + 2.30078\, ay_1 + 6.56236\, a\chi, \\ \varphi_3 &\approx .99886\, ay_2 + 2.70495\, ay_1 + 5.50583\, a\chi, \\ \varphi_4 &\approx .46753\, ay_2 + 2.71285\, ay_1 + 3.58146\, a\chi, \\ \varphi_5 &\approx .14486\, ay_2 + 1.66806\, ay_1 + 1.76929\, a\chi, \end{aligned} \tag{3.9}$$

where $\varphi_k = \varphi(x_k)$.

In order to apply the least squares method discussed above, it is necessary to choose weighting coefficients D_k' associated with the points x_k. Because of the unequal spacing of these points the ordinary Cotes integration coefficients can not be used. Instead we here require that D_k be proportional to $x_{k+1} - x_{k-1}$, where we define $x_0 = 0$, $x_6 = a$,[5] and set, for convenience, $D_k' = \frac{2}{a}(x_{k+1} - x_{k-1})$ so that $D_1' = 1/4$, $D_2' = 1/2$, $D_3' = 3/4$ and $D_4' = D_5' = 1$.

Now in accordance with the rule given in connection with (2.9), the augmented matrix of the required set of three equations in y_2, y_1, and χ, is obtained by multiplying the augmented matrix of (3.9) by the matrix formed by multiplying the kth column of the transposed coefficient matrix by D_k', viz., by the matrix

$$\begin{Vmatrix} .27778 & .61716 & .74915 & .46753 & .14486 \\ .44444 & 1.15039 & 2.02871 & 2.71285 & 1.66806 \\ 1.96052 & 3.28118 & 4.12937 & 3.58146 & 1.76929 \end{Vmatrix}.$$

In this way we obtain the equations

$$\begin{aligned} &2.05827\, ay_2 + 5.45016\, ay_1 + 12.28378\, a\chi = \\ &\quad .27778\varphi_1 + .61716\varphi_2 + .74915\varphi_3 + \\ &\qquad .46753\varphi_4 + .14486\varphi_5, \\ &5.45016\, ay_2 + 19.06646\, ay_1 + 34.87161\, a\chi = \\ &\quad .44444\varphi_1 + 1.15039\varphi_2 + 2.02871\varphi_3 + \\ &\qquad 2.71285\varphi_4 + 1.66806\varphi_5, \\ &12.28378\, ay_2 + 34.87161\, ay_1 + 75.59963\, a\chi = \\ &\quad 1.96052\varphi_1 + 3.28118\varphi_2 + 4.12937\varphi_3 + \\ &\qquad 3.58146\varphi_4 + 1.76929\varphi_5. \end{aligned} \tag{3.10}$$

Solving for y_2, y_1 and χ,[6] we have the general solution to problem 1a in the form

$$\begin{aligned} ay_2 &= -1.58627\varphi_1 + 1.23571\varphi_2 + 1.86635\varphi_3 - \\ &\qquad .80421\varphi_4 - 1.73238\varphi_5, \\ ay_1 &= -.26915\varphi_1 - .03229\varphi_2 + .17676\varphi_3 + \\ &\qquad .29758\varphi_4 + .16028\varphi_5, \\ a\chi &= .40783\varphi_1 - .14249\varphi_2 - .33017\varphi_3 + .04078\varphi_4 \\ &\qquad + .23096\varphi_5. \end{aligned} \tag{3.11}$$

As an application, we investigate the distribution of charge induced on a long, uncharged, perfectly conducting strip which is placed in a uniform electrostatic field of intensity E, perpendicular to the center line of the strip and parallel to its surface. In this case $\varphi(x) = (a-x)E$, and, substituting $\varphi_1 = aE$, $\varphi_2 = .875aE$, $\varphi_3 = .75aE$, $\varphi_4 = .5aE$, and $\varphi_5 = .25aE$ in (3.11), we obtain $y_2 = .05954\,E$, $y_1 = .02403\,E$, $\chi = .11366\,E$. A table of values of the approximate solution $\bar{\sigma}(x)$ is easily computed with the aid of the Lagrangean interpolation coefficients tabulated in Crout's paper.[1]

The exact solution is known to be

$$\sigma(x) = \frac{a-x}{2\pi\sqrt{x(2a-x)}}\, E.$$

In the following table we compare the exact values $\sigma(x)$ with the computed approximation $\bar{\sigma}(x)$ over a half-width of the strip.

x/a	$\bar{\sigma}(x)/E$	$\sigma(x)/E$	$(\sigma-\bar{\sigma})/\sigma$
.05	.48204	.48422	.0045
.1	.32792	.32861	.0021
.2	.21265	.21221	−.0021
.3	.15655	.15600	−.0035
.4	.11970	.11937	−.0028
.5	.09196	.09189	−.0008
.6	.06952	.06946	−.0009
.7	.04985	.05005	.0040
.8	.03229	.03249	.0062
.9	.01588	.01600	.0075
1.0	.00000	.00000	.0000

Near $x = 0$, we find from the exact solution that

$$\sigma(x) \approx \frac{E}{2\pi\sqrt{2}}\left(\frac{x}{a}\right)^{-\frac{1}{2}} \doteq .11254\, E\left(\frac{x}{a}\right)^{-\frac{1}{2}}.$$

Comparison of the coefficient with the computed value of χ indicates that the "limiting" error at the edge of the strip is less than 1%.

b. *Suppose that the external field is symmetrical with respect to a plane perpendicular to the strip at its center line.* It follows that $\varphi(x) = \varphi(2a-x)$. In this case we set $s(x) = \chi\{(x/a)^{-\frac{1}{2}} + (2 - x/a)^{-\frac{1}{2}}\}$ and approximate $\sigma(x)$ by the combination of $s(x)$ and a fourth degree polynomial $y(x)$ specified by its values y_2, y_1, y_0, y_1, and y_2, at the points $x = 0$, $a/2$, a, $3a/2$, and $2a$, respectively. The polynomial can now be written in the form

$$y(x) = \sum_{i=0}^{2} \overline{\overline{K}}_i(\lambda) y_i,$$

where $\lambda = 2(x/a - 1)$ and $\overline{\overline{K}}_i(\lambda) = K_i(\lambda) + K_{-i}(\lambda)$. Proceeding as in part *a*, the equations

$$\varphi(x_k) \approx -2\int_0^{2a} \{s(\xi) + y(\xi)\} \log\left|\frac{\xi - x_k}{\xi - a}\right| d\xi, \qquad k = 1, \; . \; . \; ., 5,$$

are obtained in the form

(3.12)

$$\varphi_1 \approx .54648\, ay_2 - .54939\, ay_1 - 2.76769\, ay_0 - 1.58216\, a\chi,$$

$$\varphi_2 \approx .67112\, ay_2 + .42990\, ay_1 - 2.93845\, ay_0 - 1.01711\, a\chi,$$

$$\varphi_3 \approx .48084\, ay_2 + 1.09197\, ay_1 - 2.83832\, ay_0 - .69117\, a\chi,$$

$$\varphi_4 \approx .14615\, ay_2 + 1.14969\, ay_1 - 1.81909\, ay_0 - .28149\, a\chi,$$

$$\varphi_5 \approx .02020\, ay_2 + .40336\, ay_1 - .54990\, ay_0 - .06747\, a\chi.$$

It is obvious from physical considerations that the induced charge distribution is indeterminate unless the total charge on a unit length of the strip is specified. Hence, if σ_T is the total charge per unit length, we have the additional condition that

$$\sigma_T = \int_0^{2a} \{s(\xi) + y(\xi)\} d\xi$$

or

$$\sigma_T = .31111\, ay_2 + 1.42222\, ay_1 + .26667\, ay_0 + 5.65685\, a\chi. \tag{3.13}$$

Using (3.13) to arbitrarily eliminate χ from (3.12), applying the method of least squares of Problem 1a to the resultant equations, and solving the three equations so obtained for y_2, y_1, and y_0, we obtain the solution to Problem 1b in the form

(3.14)

$$ay_2 = -2.71376\varphi_1 + 3.08414\varphi_2 + 2.12828\varphi_3 - 3.58497\varphi_4 - 2.00920\varphi_5 - .14679\sigma_T,$$

$$ay_1 = -1.02359\varphi_1 + .45929\varphi_2 + .67631\varphi_3 - .19349\varphi_4 - .21404\varphi_5 - .13325\sigma_T,$$

$$ay_0 = -.94462\varphi_1 + .65788\varphi_2 + .52153\varphi_3 - .85840\varphi_4 - .49188\varphi_5 - .13077\sigma_T,$$

$$a\chi = .45111\varphi_1 - .31610\varphi_2 - .31167\varphi_3 + .28627\varphi_4 + .18750\varphi_5 + .22452\sigma_T,$$

the last equation being obtained from (3.13).

As an application, suppose that a charge of σ_T per unit length is placed on a long, perfectly conducting strip, no external field being present. We require the steady state charge distribution. In this case $\varphi(x) = 0$, and we obtain from (3.14) the values $ay_2 = -.14679\sigma_T$, $ay_1 = -.13325\sigma_T$, $ay_0 = -.13077\sigma_T$, and $a\chi = .22452\sigma_T$.

The exact solution is known to be

$$\sigma(x) = \frac{\sigma_T}{\pi\sqrt{x(2a-x)}}.$$

In the following table the exact values $\sigma(x)$ and the computed approximate values $\bar{\sigma}(x)$ are compared over a half-width of the strip.

x/a	$a\bar{\sigma}(x)/\sigma_T$	$a\sigma(x)/\sigma_T$	x/a	$a\bar{\sigma}(x)/\sigma_T$	$a\sigma(x)/\sigma_T$
.05	1.02033	1.01941	.6	.34736	.34730
.1	.73037	.73025	.7	.33371	.33368
.2	.53023	.53052	.8	.32487	.32487
.3	.44551	.44572	.9	.31988	.31991
.4	.39782	.39789	1.0	.31826	.31831
.5	.36758	.36755			

It is seen that all errors involved are less than one tenth of one percent of the true values.

Referring to the exact solution, it is seen that, near $x = 0$, $\sigma(x) \approx .22508\ (\sigma_T/a)(x/a)^{-\frac{1}{2}}$, so that the "limiting error" at the edge is less than one-fourth of one percent.

c. Since any continuous function defined over $(0,\ 2a)$ can be resolved into the sum of two continuous functions, one of which is symmetrical, the other antisymmetrical, about $x = a$, it follows by superposition that we can use (3.11) and (3.14) to obtain the approximate distribution of charge induced by an arbitrary field of the type described in the statement of the problem. Then, by the use of further superposition and approximate integration, the potential or field intensity at an arbitrary point in space can be readily determined. In this sense we have obtained an approximate solution to the two-dimensional Dirichlet problem for an infinite strip.

The integral equation (3.1) can be obtained formally by integrating both sides of the equation

$$E(x) = \int_0^{2a} 2\sigma(\xi)\frac{d\xi}{\xi - x}, \tag{3.15}$$

where $E = \frac{d\varphi}{dx}$, solutions to which have been given under certain restrictions by Betz,[7] Fuchs,[8] Schröder,[9] and others. We have deliberately chosen this equation because of this fact, permitting a verification of the approximate results obtained. However, it is seen that the methods given here are applicable to very large classes of linear integral equations, whether of first or second type, and also to many integro-differential equations.

Much of the data tabulated in the solution of Problem 1 can be used in connection with the solution of other Dirichlet or Neumann type problems associated with various plane figures bounded by straight lines. For example, in order to determine the charge distribution on a parallel plate condenser constructed of long plates of finite breadth 2a and separation h it is necessary to solve the integral equation[10]

$$\varphi(x) = -2\int_0^{2a} \sigma(\xi)\log\left|\frac{\xi - x}{\xi - a}\right| d\xi + \int_0^{2a} \sigma(\xi)\log\frac{(\xi - x)^2 + h^2}{(\xi - a)^2 + h^2}\,d\xi, \tag{3.16}$$

where $\varphi(x) = 0$ and $\int_0^{2a} \sigma(\xi)d\xi = \sigma_T$, the total charge per unit length on each plate. An approximate solution where $h = a/2$ has been obtained by the writer using the methods of this paper.[10] The approximate charge distribution curve for a half plate is given in Fig. 1. Using this solution it is not difficult to obtain the capacity of the condenser or the potential or field intensity at an arbitrary point in space.

As a final application we set the following problem from the theory of elasticity:

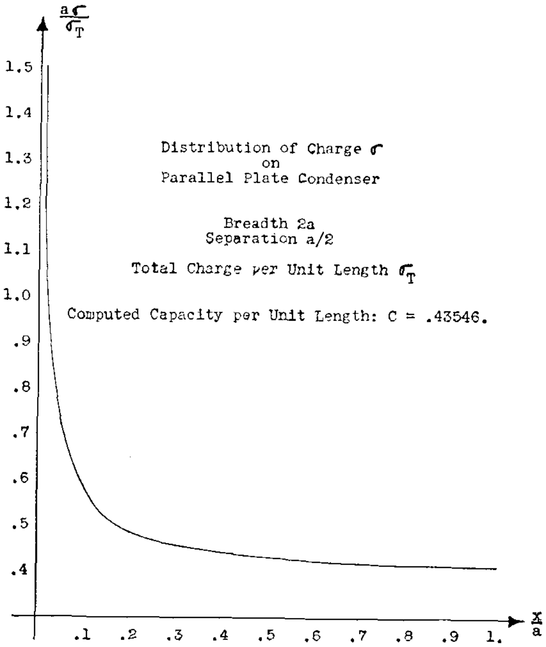

Fig. 1.

Problem 2. A long bar of equilateral triangular cross section is twisted by couples applied at the ends. Determine the stress function and investigate the shear stress distribution in a cross section of the bar. It is well known[11] that the stress function Φ satisfies the differential equation $\nabla^2\Phi = -2G\Theta$, where ∇^2 is the two-dimensional Laplace operator, and vanishes at the boundary of the cross-section. G and Θ are constants, G being the modulus of rigidity and Θ the angle of twist per unit length of the bar. If we represent the stress function in the form

$$\Phi = \varphi - \frac{G\Theta}{2}r^2, \tag{3.16}$$

where r is measured from the axis of the bar in a plane perpendicular to the axis, it is necessary to determine a function φ, satisfying Laplace's equation, such that, along the boundary of a cross section,

$$\varphi - \frac{G\Theta}{2}r^2 = 0. \tag{3.17}$$

It is seen that the determination of φ is analogous to the determination of the electrostatic potential inside the boundary formed by three infinite conducting strips coincident with the faces of the bar, if the system is placed in an electrostatic field such that the potential at a point inside or on the boundary, due to this field, is given by $-G\Theta r^2/2$. It will be convenient to preserve this analogy in our solution to the problem. Thus, as in Problem 1, we determine a distribution of (fictitious) induced charge on the strips necessary to maintain the boundary at constant potential. Then, by superposition and approximate integration, we are able to obtain the value of φ and hence, by (3.16), of the stress function, at any point inside the boundary.

It is clear that, in obtaining the potential function for the interior of the triangular boundary, it is necessary to specify the total fictitious charge per unit length on the bounding strips, the specification being, however, perfectly arbitrary since the potential inside the boundary is unchanged if to the original distribution is added any multiple of the charge distribution which would maintain the conducting surface at zero potential in the absence of an external field. For convenience we shall require that the total charge be zero.

From symmetry it is obvious that the charge distributions on the three faces will be identical and, on each face, will be symmetrical about the center line. Thus, if we denote the perpendicular distance from an edge on any face by the variable x, and consider a unit length of the system, we are to solve the integral equation

$$-\varphi(x) - 2\oint \sigma(\xi) \log \frac{r(x, \xi)}{R(\xi)}\, d\xi = \text{const.},$$

where $\varphi(x) = \dfrac{G\Theta}{2}\left\{\dfrac{a^2}{3} + (a - x)^2\right\}$, $r(x, \xi)$ denotes the distance between the points x and ξ in a plane section, and $R(\xi)$ denotes the distance between the point ξ and the point of zero potential, the integration being taken over the complete triangular contour. Taking the locus of zero potential at the center of one of the faces and setting the constant equal to $-G\Theta a^2/6$, the equation can be written in the form

$$\begin{aligned} \frac{G\Theta}{2}(a-x)^2 = -2\int_0^{2a} \sigma(\xi) \log\left|\frac{\xi - x}{\xi - a}\right| d\xi - \\ \int_0^{2a} \sigma(\xi) \log \frac{\xi^2 - x\xi + x^2}{\xi^2 - a\xi + a^2}\, d\xi - \\ \int_0^{2a} \sigma(\xi) \log \frac{\xi^2 - (2a-x)\xi + (2a-x)^2}{\xi^2 - a\xi + a^2}\, d\xi. \end{aligned} \tag{3.18}$$

Since the angle opening at the corners is $5\pi/3$ the induced charge $\sigma(x)$ must have singularities of order $1 - \dfrac{\pi}{5\pi/3} = 2/5$ at $x = a$ and $x = 2a$. Also, by symmetry, $\sigma(x) = \sigma(2a - x)$. Because of the necessity of a considerable amount of approximate integration in the present problem, it is convenient to define the singular approximation in such a way that it will vanish over a large part of the interval $(0, 2a)$ but will have sufficient regularity in the open interval to enable the difference between the functions $\sigma(x)$ and $s(x)$ to be approximated by a polynomial $y(x)$. Such a function, having a continuous first derivative in the open interval, is obtained if we set

$$s(x) = \begin{cases} \left(\dfrac{x}{a}\right)^{-\frac{2}{5}} + \dfrac{8}{5}(4)^{\frac{2}{5}}\left(\dfrac{x}{a}\right) - \dfrac{7}{5}(4)^{\frac{2}{5}}, & 0 < x \leqslant a/4, \\ 0, & a/4 \leqslant x \leqslant 7a/4, \\ (2 - x/a)^{-\frac{2}{5}} - \dfrac{8}{5}(4)^{\frac{2}{5}}\left(\dfrac{x}{a}\right) + \dfrac{9}{5}(4)^{\frac{2}{5}}, & 7a/4 \leqslant x < 2a. \end{cases} \tag{3.19}$$

This function is formed, over the interval $(0, a/4)$, by subtracting from the function $(x/a)^{-\frac{2}{5}}$ the ordinates of the tangent line at $x = a/4$, and, over the interval $(7a/4, 2a)$, by subtracting from the function $(2 - x/a)^{-\frac{2}{5}}$ the ordinates of the tangent line at $x = 7a/4$.

Now, employing the notation of Problem 1, we set

$$y(x) = \sum_{i=0}^{2} \bar{\bar{K}}_i(\lambda) y_i, \tag{3.20}$$

where $\bar{\bar{K}}_i(\lambda) = K_i(\lambda) + K_{-i}(\lambda)$, $\lambda = 2(x/a - 1)$, and y_2, y_1, and y_0 are the undetermined ordinates of $y(x)$ at $x = 0$, $a/2$, and a, respectively, and require that $\bar{\sigma}(x) = s(x) + y(x) \approx \sigma(x)$. Then it follows that

$$\frac{G\Theta}{2}(a-x)^2 \approx -2\oint \{s(\xi) + y(\xi)\} \log \frac{r(x, \xi)}{R(\xi)}\, d\xi,$$

where, because of the restriction on the total charge,

$$\int_0^{2a} \sigma(\xi) d\xi \approx \int_0^{2a} \{s(\xi) + y(\xi)\} d\xi = 0.$$

Next we require that

$$\frac{G\Theta}{2}(a - x_k)^2 \approx -2\oint \{s(\xi) + y(\xi)\} \log \frac{r(x_k, \xi)}{R(\xi)}\, d\xi, \quad k = 1, \ldots, 5, \tag{3.21}$$

corresponding to equations (2.9), where the points x_k are given, as before, by $x = 0$, $a/8$, $a/4$, $a/2$, and $3a/4$, respectively. The integrations can be carried out for the most part by approximate methods, the work being arranged systematically in terms of matrices,[10] yielding the system of equations

(3.22)

$$1.06226y_2 - .79070y_1 - 3.48779y_0 + 2.98691\chi = .50000\, G\Theta a,$$

$$.99668y_2 + .65565y_1 - 3.67312y_0 + 1.22791\chi = .38281\, G\Theta a,$$

$$.68148y_2 + 1.35204y_1 - 3.38659y_0 + .65509\chi = .28125\, G\Theta a,$$

$$.21117y_2 + 1.30639y_1 - 2.05592y_0 + .21539\chi = .12500\, G\Theta a,$$

$$.03484y_2 + .41273y_1 - .57133y_0 + .04688\chi = .03125\, G\Theta a,$$

together with the condition

(3.23)

$$\int_0^{2a} \bar{\sigma}(\xi)d\xi = .31111y_2 + 1.42222y_1 + .26667y_0 + .40626\chi = 0.$$

Using (3.23) to eliminate χ from (3.22) and applying the least squares method of Problem 1, we obtain the three equations

(3.24)

$$.40320y_2 + 3.24045y_1 + .92688y_0 = -\,.09868\, G\Theta a,$$

$$3.24045y_2 + 39.29219y_1 + 24.80951y_0 = -\,2.22493\, G\Theta a,$$

$$.92688y_2 + 24.80951y_1 + 33.56787y_0 = -\,2.63692\, G\Theta a,$$

which give $y_2 = .11808\, G\Theta a$, $y_1 = -\,.02757\, G\Theta a$, $y_0 = -\,.06144\, G\Theta a$, and $\chi = .04642\, G\Theta a$, the value of χ being obtained from (3.23).

These values, in connection with (3.19) and (3.20), serve to determine the function $\bar{\sigma}(x)$. Now, by approximate integration, it is an easy matter to determine the value of the function φ and hence of the stress function $\Phi = \varphi - G\Theta r^2/2$ at any point inside the contour. For since $\varphi = G\Theta a^2/6$ at the center of a face, the value of φ at any point P is given by

$$\varphi(P) - G\Theta a^2/6 \approx -2\oint \bar{\sigma}(\xi) \log \frac{r_P(\xi)}{R(\xi)}\, d\xi,$$

where $r_P(\xi)$ is the distance between the point P and the point ξ, and $R(\xi)$ is the distance between the point ξ and the reference point at the center of a face.

For example, the value of φ at the center of the bar is given approximately by the integral

$$\varphi(C) \approx G\Theta a^2/6 - 2\int_0^{2a} \bar{\sigma}(\xi) \log \frac{\sqrt{(\xi-a)^2+a^2/3}}{|\xi-a|}\, d\xi - 2\int_0^{2a} \bar{\sigma}(\xi) \log \frac{(\xi-a)^2+a^2/3}{\xi^2-a\xi+a^2}\, d\xi.$$

This is evaluated easily by approximate methods with the help of matrices tabulated earlier in the problem[10] and gives $\varphi(C) = .22254\, G\Theta a^2$. Since $r = 0$ at this point, referring to (3.16), this gives directly the value of the stress function at the point. The exact value[11] is $\frac{2}{9}\, G\Theta a^2$, so that the error is less than 0.15%.

Finally, we compute the value of the shear stress τ,

$$\tau = -\frac{d\Phi}{dr} = G\Theta r - \frac{d\varphi}{dr}$$

at the center of a face, where the maximum stress occurs. Now the integral

$$\bar{E}(P) = -2\oint \sigma(\xi)\, \frac{\cos \vartheta_P(\xi)}{R_P(\xi)}\, d\xi,$$

where P is a point on the boundary, $\vartheta_P(\xi)$ is the angle included between the normal at P and the line joining P and ξ, and $R_P(\xi)$ is the distance between the points P and ξ, gives the mean value of the interior and exterior limits of the normal gradient of φ at P.[12] Since the total jump at the boundary is given by 4π times the charge density at P,[12] it follows that the required interior limit is given by $\bar{E}(P) + 2\pi\sigma(P)$, so that the shear stress τ at P is given by

$$\tau(P) = G\Theta r(P) - \bar{E}(P) - 2\pi\sigma(P).$$

In particular, if P_0 is at the center of a face we have, because of symmetry and since $\vartheta = 0$ on that face,

$$\bar{E}(P_0) = -4\int_0^{2a} \bar{\sigma}(\xi)\, \frac{\xi d\xi}{\xi^2 - a\xi + a^2},$$

which gives, by approximate integration, $\bar{E}(P_0) = .09914\, G\Theta a$. Also, $r(P_0) = G\Theta a/\sqrt{3}$ and $\bar{\sigma}(P_0) = y_0 = -\,.06144\, G\Theta a$, so that we obtain $\tau(P_0) = .86424\, G\Theta a$. The true value[11] is $\sqrt{3}G\Theta a/2 \doteq .86603\, G\Theta a$, the error thus being less than 0.21%.

The exact solution to problem 2 can be found very easily by semi-inverse methods.[11] However, the application of such methods is restricted to very special types of cross-sections. The present method obviously requires considerably more computation but may be of practical interest in cases where experimental results are not sufficiently accurate, since it is a direct method and can be applied to any prismatical bar.

4. *Conclusion.* The purpose of this paper is to present a practical method of obtaining numerical solutions to singular integral equations. We have not been concerned with existence and uniqueness theory, which has been well developed elsewhere.

Although a certain amount of calculation is necessarily involved, the work can be organized and reduced principally to matrix multiplication and similar operations for which the modern computing machine is well adapted. Much simplification results from the use of the Lagrangean form of the polynomial in connection with published tables of Lagrangean coefficients.[1]

We have deliberately chosen problems for which the exact solutions are known. However, a large variety of important problems arising in static field theory, air-foil theory, elasticity, etc., which can be set up in a natural way in terms of singular integral equations, are at present unsolved.

The principal practical difficulty remaining concerns the determination of the existence and nature of the singularities in the unknown function. In many cases such information can be obtained from physical considerations, as in Problems 1 and 2. Otherwise, one can assume the existence of a singularity of order t at a certain point and determine t by requiring that the integral equation be satisfied at that point, or that both sides of the equation have the same asymptotic behavior in the neighborhood of the point.

No expression has as yet been devised for estimating the error inherent in the present method of approximation. Since the determination of such an expression seems to involve the solution of a second integral equation, and since error estimates are generally of limited applicability, particularly when the solution is unbounded or the data are empirical, a further study of the problem has not been made. However, substitution of the computed values of the parameters in the m equations involved in the least square procedure gives an indication as to how well the integral equation is satisfied at the corresponding m points in the interval of integration. If these points are chosen judiciously, a physical interpretation of the variation in the differences between the two sides of the equation will frequently indicate the degree of approximation obtained.

Finally, we point out the fact that many singular integral equations in which the range of integration is infinite can be transformed to types to which the methods outlined will apply. For example, to determine the induced charge distribution on an infinite half-plate it is necessary to solve the integral equation

$$\varphi(x) = -2\int_0^\infty \sigma(\xi)\log\left|\frac{\xi-x}{\xi-1}\right| d\xi$$

(where the locus of zero potential is taken to be the line $x = 1$). If we set $\xi = \tau/(2a-\tau)$, $x = t/(2a-t)$, and $\kappa(t) = (2a-t)^{-2}\,\sigma\left(\frac{t}{2a-t}\right)$, the equation takes the form

$$\varphi\left(\frac{t}{2a-t}\right) = -4a\int_0^{2a}\kappa(\tau)\log\left|\frac{\tau-t}{\tau-a}\right| d\tau +$$
$$4a\log(2-t/a)\int_0^{2a}\kappa(\tau)\,d\tau,$$

the approximate solution to which can be readily obtained with the use of the data computed for Problem 1.

5. *Acknowledgment.* The author wishes to express his appreciation to Professor P. D. Crout for valuable suggestions and criticisms in connection with the preparation of this paper.

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[1] P. D. Crout, *An Application of Polynomial Approximation to the Solution of Integral Equations Arising in Physical Problems*, Journal of Mathematics and Physics, M. I. T., Vol. XIX., No. 1 (1940), pp. 34–92.

[2] Hildebrand and Crout, *A Least Square Procedure for Solving Integral Equations by Polynomial Approximation*, Journal of Mathematics and Physics, M. I. T., Vol. XX, No. 3 (1941), pp. 310–35.

[3] The data given in this paper (except where exact) were obtained by omitting a certain number of decimal places from the original data which were retained to ten significant figures on a ten bank computing machine.

[4] The matrix multiplication can be carried out quickly on a modern computing machine, each element of the product matrix being obtained by one continuous operation.

[5] For equal spacings this would give the trapezoidal formula.

[6] The solution is obtained conveniently on a computing machine by Gauss' method, or by one of its refinements. See, for example, Crout, *A Short Method for Evaluating Determinants, and Solving Systems of Linear Equations with Real or Complex Coefficients*, Trans. Am. Inst. E. E., August, 1941.

[7] A Betz, *Beiträge zur Tragflügeltheorie*, Dissertation, Gottingen, 1919.

[8] R. Fuchs, *Theorie der Luftkräfte*, Berlin, 1935, pp. 54–60.

[9] K. Schröder, *Über eine Integralgleichung erster Art der Tragflügeltheorie*, Sitzungsberichte der Preussischen Akademie der Wissenschaften (1938) XXX.

[10] *The Solution by Polynomial Approximation of Singular Integral Equations Arising in Static Field Theory*, Dissertation, Massachusetts Institute of Technology, 1940.

[11] S. Timoshenko, *Theory of Elasticity*, McGraw-Hill (1934), pp. 236–7.

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THE INNER CHAPTERS OF PAO-P'U-TZŬ

By Tenney L. Davis and Ch'ên Kuo-fu

THE INNER CHAPTERS OF PAO-P'U-TZŬ

BY TENNEY L. DAVIS AND CH'ÊN KUO-FU

Presented December 10, 1941. Received February 28, 1941.

1. With the present publication,[1] what is believed to be all of the material relative to alchemy in the Inner Chapters of *Pao-p'u-tzŭ* 抱朴子 (*Ko Hung* 葛洪) becomes available in English translation. A translation by the late Dr. *Wu Lu-ch'iang* 吳魯強 of the whole of Inner Chapters IV and XVI, On the Gold Medicine[2] and On the Yellow and the White, has been published, with a discussion, in *Proc. Amer. Acad. Arts and Sciences*, **70**, 221–284 (1935). Those two chapters are of the utmost importance for the understanding of *Ko Hung's* alchemy. They contain little or nothing of the theory of alchemy but are evidently the writing of a man accustomed to practical chemical manipulations, familiar with the behavior of his reagents, intent upon the preparation of *chin tan* 金丹 by the taking of which a man would become a *hsien* 仙 (immortal), trying to prepare authentic gold and silver by chemical processes from base metal, believing that certain of his materials had the properties of an elixir or ferment or Philosopher's Stone for the conversion of additional base metal, and fully aware of the possibility of imitating noble metal by chemical means but not satisfied with the imitative art and insisting upon genuine transmutation as his object. English translations by *Ch'ên Kuo-fu* 陳國符 of the whole of Inner Chapters VIII and XI, Overcoming Obstructions and On *hsien* Medicines,[3] paraphrases, abstracts, or summaries of the rest of the twenty Inner Chapters, new material on the biography and autobiography of *Ko Hung*, and certain material relative to the sequence of teachers from whom he derived his alchemy are published herewith.

2.) The Inner Chapters of *Pao-p'u-tzŭ* are devoted to the various magical means by which one may become a *hsien* and to various means, largely magical, by which one may accomplish the extraordinary things of which *hsien* are supposed to be capable. The best of the *hsien* medicines are *huan tan* 還丹 and *chin i* 金液 (gold fluid), edible and potable gold—and jade and mica which are also eternal—by the ingestion of which a man becomes an immortal. The belief that these materials produce immortality is obviously magical, probably very ancient, and it supplies a motive for alchemy. Natural gold may be used for the purpose, and its use in this manner is merely magic, but the artificial production of authentic gold by chemical means is alchemy, and the search for it commenced after chemical means for its prosecution were already available. We find magic before alchemy to supply the motive, and chemistry before alchemy to supply the means. While the best *hsien* medicines are made from mineral substances, lesser medicines are made from vegetable materials, and it is undoubtedly the case that some of those which *Pao-p'u-tzŭ* describes have actual physiological effects. Other means which he describes for attaining longevity and for assisting the quest of *tao* 道, though none of them are sufficient to make a man a *hsien*, are abstinence from grains, directing the *ch'i* 氣 (ethereal essences) of one's body,[4] *tao yin* 導引 (deep breathing, certain exercises of the hands and feet, etc.), and the art of the sleeping room (suitable sexual satisfaction). He further describes many *fu* 符 (magical drawings, charms, talismans) by the use of which marvelous deeds are accomplished.

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[1] We wish to make grateful acknowledgment to the American Academy of Arts and Sciences of a grant from the Permanent Science Fund for the purpose of defraying the expenses of the preparation of the translation, to the Harvard-Yenching Institute for the use of the Chinese type, and to Professor James R. Ware of Harvard University for reading the manuscript, for comparing the translation with the text of *Pao-p'u-tzŭ*, and for valuable criticism and suggestions. Professor Ware states that *chin tan* in this text must be translated "*chin* and *tan*" or "*chin* or *tan*" according to the context.

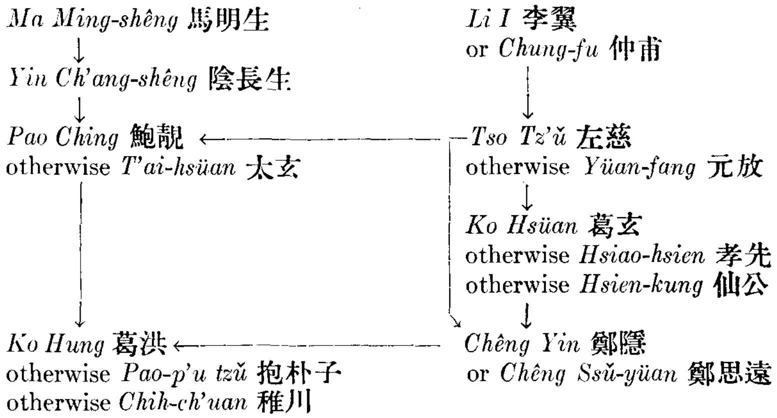
[2] The translation of this title ought to be corrected to read "On the Gold (Fluid) and (Returned) Medicine."

[3] Two editions of *Pao-p'u-tzŭ* have been used, the *ch'ung-wên shu-chü* 崇文書局 edition and that which Dr. *Wu* used, the *Ch'êng-hsün shu-yüan* 承訓書院 in *Ssŭ-pu ts'ung-k'an* 四部叢刊 reprinted and published by The Commercial Press, Ltd., Shanghai.

[4] Cf. H. Maspero, Les procédés de "nourrir le principe vital," *Jour. asiatique*, **229**, 117–252, 353–430.

TEACHERS OF KO HUNG

3.) *Ko Hung* learned alchemy from *Chêng Yin*, a disciple of his own paternal great uncle, *Ko Hsüan*, and from *Pao Ching*, who gave him his daughter in marriage. The sequence of teachers from whom these men derived their alchemy, so far as we have been able to learn it, is indicated below.


Ma Ming-shêng 馬明生
Yin Ch'ang-shêng 陰長生
Pao Ching 鮑靚
otherwise *T'ai-hsüan* 太玄
Ko Hung 葛洪
otherwise *Pao-p'u tzŭ* 抱朴子
otherwise *Chih-ch'uan* 稚川
Li I 李翼
or *Chung-fu* 仲甫
Tso Tz'ŭ 左慈
otherwise *Yüan-fang* 元放
Ko Hsüan 葛玄
otherwise *Hsiao-hsien* 孝先
otherwise *Hsien-kung* 仙公
Chêng Yin 鄭隱
or *Chêng Ssŭ-yüan* 鄭思遠

4.) **Yin Ch'ang-shêng** (from Biographies of *shên hsien* 神仙 quoted by *T'ai-p'ing-yü-lan* 太平御覽). *Yin Ch'ang-shêng* was a native of *Hsin-yeh* 新野 (at present a District in Honan Province) and belonged to the clan of the Empress *Yin* of the Later *Han* 漢 dynasty (25–220 A. D.). Although he was accustomed to wealth and to holding official position, yet he did not like them. Hearing that *Ma Ming-shêng* had obtained the art of delivering from the human world, he sought after him, and, after he met him, he served him as a coachman for ten and more years without any negligence. *Ma Ming-shêng* said: "You have really achieved the *tao* already!" They then went into Mt. *Ch'ing-ch'êng* 青城 (in the *Kuan* 灌 District, Ssŭ-ch'uan Province) where *Ma Ming-shêng* gave him *T'ai ch'ing shên tan ching* 太清神丹經 (Supreme Clear Divine Medicine Book). He afterwards took leave and became a *hsien* in Mt. *P'ing-tu* 平都 (in the *Fêng-tu* 酆都 District, Ssŭ-ch'uan Province).

5.) **Pao Ching** (from Biographies of *shên hsien*, quoted by *T'ai-p'ing-yü-lan*. *Pao Ching*, whose *tzŭ* 字 (agnomen) was *T'ai-hsüan*, was a native of *Lang-yeh* 琅邪 (a *chün* 郡 in present South Shantung). He was living at the time of the reign of *Chin Ming-ti* 晉明帝 (323–325 A. D.). *Yin chün* 陰君 handed down to him *Shih chieh fa* 尸解法 (Method of Becoming Immortal through Death). According to other information, *Pao Ching* was a native of *Shang-tang* 上黨 (a *chün* in present South Shansi) and a descendant of a *ssŭ-li* 司隸 of the *Han* dynasty.

6.) (From *Chin shu* 晉書). *Pao Ching*, whose *tzŭ* was *T'ai-hsüan*, was a native of *Tung-hai* 東海 (a *chün* in present South Shantung). He studied outer and inner learnings, and understood astronomy and the plans of the Yellow River and the River *Lo* 洛 (magic diagrams said to have been revealed supernaturally through the agency of the two rivers). He received a slight promotion to *chung pu tu wei* 中部都尉 of *Nan-yang* 南陽 (a *chün* in present South Honan), and afterwards was *t'ai shou* 太守 of *Nan-hai* 南海 (a *chün* in present Middle Kuangtung).

7.) (from *Yün chi ch'i ch'ien* 雲笈七籤). *Pao Ching*, whose *tzŭ* was *T'ai-hsüan*, was a native of *Ch'ên-liu* 陳留 (a *chün* in present Middle Honan). He understood the recipes in our books and fortune-telling. He was a student of *Tso Yüan-fang* 左元放 and from him he received *Chung pu fa* 中部法 and the essentials of the impeachment and summons of the three Emperors and the five sacred mountains. He practiced these most carefully and was able to exert authority over supernatural beings, to close mountains, and to suppress devils.

8.) **Tso Tz'ŭ** (from *T'ai-p'ing-yü-lan*). *Tso Tz'ŭ*, whose *tzŭ* was *Yuan-fang*, was a native of *Lu-chiang* 廬江 (a *chün* in present Middle Anhui). He understood the Five Canonical Books and astrology. He learned *tao* after he saw that the *Han* dynasty was falling into decay. Meditating on Mt. *T'ien-chu* 天柱 (in the *Yü hang* 餘杭 District, Chekiang Province), he obtained in a stone-room the *Chiu tan chin i ching* 九丹金液經 (Book of Nine-fold Medicine and the Gold Fluid) which was *T'ai ch'ing chung ching fa* 太清中經法. *Li Chung-fu* was his teacher and *Ko Hsüan* was his disciple. Having heard (his reputation), *Ts'ao Ts'ao* 曹操 summoned him and asked him why he had learned *tao*. He did not answer. *Ts'ao Ts'ao* became angry and tried to kill him by a secret plot; he gave a banquet for him, but suddenly he disappeared. At the end of the period *Chien-an* 建安 (196–219 A. D.) he crossed the Yangtze River in search of a mountain, in a cave of which he might live. Afterwards he lived in Mt. *Hsiao-kua* 小括 with very good countenance.

9.) Although *Tso Tz'ŭ* was the teacher of *Ko Hsüan* who taught *Chêng Yin* who taught *Ko Hung*, there is a passage of Inner Chapter XVI[5] which indicates that *Tso Tz'ŭ* had contact with *Ko Hung's* immediate teacher. "*Chêng chün* 鄭君 said that he and *Tso chün* 左君 had attempted the compounding with success on *T'ung shan* 銅山 (Copper Mountain) in *Lu-chiang* 廬江 (*Lu* River)."

10.) **Ko Hsüan.** *Hsien-kung* 仙公 is mentioned in Inner Chapter IV[6] where certain books are named which he received from *Tso Yüan-fang* and passed on to *Chêng chün* who gave them to *Ko Hung*.

11.) (from the Biographies of *shên hsien*, quoted by *T'ai-p'ing-yü-lan*). *Ko Hsüan*, whose *tzŭ* was *Hsiao Hsien*, received *Chiu tan chin i ching* from *Tso Tz'ŭ*. He constantly took *shu* 朮 (a medicinal plant, *Atractylis ovata*, Thunb.).

12.) (from *San tung chu nang* 三洞珠囊, quoted by *T'ai-p'ing-yü-lan*). *Ko Hsüan* was the paternal great uncle of *Pao-p'u-tzŭ*, and the teacher of *Chêng Ssŭ-yüan*. People of the time did not know where he lived. It was said that the Letter of the *hsien* of the Eastern Sea called him *Hsien-kung*.

13.) **Chêng Yin.** *Chêng chün* is mentioned in Inner Chapter IV[7] where his opinions relative to the method of preparing the gold medicine are reported, and in Inner Chapter XVI[8] where several books which he gave to *Ko Hung* are named and where an extremely important conversation between master and disciple is described which defines clearly the objectives of alchemy. Inner Chapter XIX, Extensive Reading, contains a considerable account of *Chêng chün* and of *Ko Hung's* relations with him (see translation below).

14.) (from *Yün chi ch'i ch'ien*). *Chêng Ssŭ-yüan* was a Confucianist when he was young. He was proficient in calendar-making 律厯, and fortune telling 候緯. When he was older, he was a student of *Ko Hsiao-hsien* 葛孝先 from whom he received (learned) *Chêng i fa wên* 正一法文, *San huang nei wên* 三皇内文, *Wu yo chên hsing t'u* 五嶽眞形圖 (Diagram of the True Shapes of the Five Sacred Mountains), *T'ai ch'ing chin i ching* 太清金液經 (Supreme Clear Gold Fluid Book), and *Tung hsüan wu fu* 洞玄五符 (Five Charms of *Tung hsüan*). Afterwards he lived on *Mt. Ma-chi* 馬迹 in *Lu-chiang* 廬江.

BIOGRAPHY OF KO HUNG

15.) (from *Chin shu*). *Ko Hung*, whose *tzŭ* was *Chih-ch'uan*, was a native of *Chü-jung* 句容.[9] (now a district of Kiangsu Province) in *Tan-yang* 丹楊 (a *chün*, now South Kiangsu). His grandfather, *Ko Hsi* 葛系, was a *ta hung lu* 大鴻臚 under the *Wu* 吳 dynasty (222–280 A. D.). His father, *Ko T'i* 葛悌, after the state of *Wu* was conquered, was a *t'ai shou* of *Shao-ling* 邵陵 (a *chün*, now Southwest Hunan) under the *Chin* 晉 dynasty. When young, *Ko Hung* studied diligently. His family was poor, so he gathered firewood by himself for the purchase of paper and brushes. At night he studied. He was famous for his Confucianist learning. By nature he had but few desires. As for games, he did not know the number of rows on a chessboard or the names of the pieces in the (game) *ch'u-p'u* 摴蒱. He was a man of no eloquence. Disliking glory and profit (official rank and wealth), he lived privately, and never had social intercourse. When he met *Ho Yu-tao* 何幼道 and *Kuo Wên-chü* 郭文舉 in Mt. *Yü-hang* 餘杭, he merely looked at them but did not converse with them. Whenever he was seeking for books or inquiring the meaning (of a passage or book), he did not consider many thousands of *li* 里 a long journey.

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[5] trans. *Wu*, *loc. cit.*, p. 256.

[6] *loc. cit.*, p. 235.

[7] *loc. cit.*, pp. 235, 252. Cf. also *T'ai-p'ing-yü-lan* 663. 5a 2–3.

[8] *loc. cit.*, pp. 256, 260–261.

[9] From the autobiography in Outer Chapter L of *Pao-p'u-tzŭ*, it appears that his ancestor moved from *Lang-yeh* to *Chü-jung* during the reign of *Kuang-wu-ti* 光武帝 (25-57 A. D.) of the *Han* dynasty.

He traveled dangerous roads in the hope of being able surely to get them. Then he read many books, but preferred the arts of *tao yin* and *yang shêng* (that had been practised by) the *shên* and *hsien*.

16.) His paternal great uncle, *Ko Hsüan*, studied *tao* and achieved *hsien*-ship during the *Wu* dynasty, and was called *Ko hsien-kung*. He communicated his secret art of preparing *tan* 丹 to his disciple, *Chêng Yin*. *Ko Hung* studied under *Chêng Yin* and obtained all of his arts. Later he studied under *Pao Ching*, *t'ai shou* of *Nan-hai* and a native of *Shang-tang*. Having also studied inner learning, *Pao Ching* foresaw the future and held *Ko Hung* in great esteem. He gave him his daughter in marriage. *Ko Hung* handed down the teachings of *Pao Ching*. He was also proficient in medicine. In all his writings he carefully distinguished the true from the false. His talents were abundant.

17.) When during the era *T'ai-an* 太安 *Shih Ping* 石冰 revolted, *Ku Pi* 顧秘, *t'ai-shou* of *Wu-hsing* 吳興 (a *chün*, now North Chekiang), who was commander of volunteers, *Chou Ch'i* 周玘, and others raised an army to exterminate the rebel. *Ku Pi* gave *Ko Hung* a commission as *chiang-ping tu-wei* 將兵都尉. He attacked *Shih Ping*'s field officer and defeated him. Thus he was raised to *fu-po chiang-chün* 伏波將軍. After *Shih Ping* was suppressed, without partaking of a reward for his merit, he went directly to *Lo-yang* 洛陽 (now a district in Honan Province) to look for curious books to enlarge his learning. He saw that the empire was already in a state of disturbance. Aiming to take refuge in the south, he took the office of military adviser to *Chi Han* 嵇含, governor of *Kuang-chou* 廣州 (corresponding approximately to the present provinces of Kuangtung and Kuangsi). After *Chi Han* was murdered, he stayed in the south. He declined all appointments of the local authorities for many years. Later he returned home. (At home too) he did not take all the posts which were offered to him. *Yüan-ti* 元帝 (*Ssŭ-ma Jui* 司馬睿), who was Prime Minister at the time, appointed him his assistant 掾. Because of his merit in suppressing the rebels, he was ennobled as *Kuan-nei hou* 關內侯 (Marquis of *Kuan-nei*). At the beginning of the era *Hsien-ho* 咸和 (326–334 A. D.), *ssŭ-t'ŭ* 司徒 *Wang Tao* 王導 summoned him to fill the office of *chou-chu-pu* 州主簿. Later he was transferred to *ssŭ-t'u-yüan* 司徒掾. Afterwards he was promoted to *tzŭ-i-ts'an-chün* 諮議參軍. *Kan Pao* 干寶 was his intimate friend, and recommended him as having talent capable of writing the national history. So he was selected as *san-ch'i-ch'ang-shih* 散騎常侍 in charge of his dynasty's history, but he declined firmly to take the office.

18.) Because of old age, he desired to prepare *tan* for the achievement of long life. Hearing that cinnabar occurred in *Chiao-chi* 交阯 (a *chün*, now Tonkin, French Indo-China), he asked for the position of magistrate of *Kou-lou* 勾漏 (a district within the *chün*). Because of his high standing, the Emperor withheld his consent. He said: "It is not for glory, but only because cinnabar occurs there!" Then the Emperor consented. He set out with his son and his brother's son. When they arrived at Canton, *Têng Yo* 鄧嶽 Governor of *Kuang-chou*, detained them and did not allow them to go on. He then stayed in Mt. *Lo-fou* 羅浮 to prepare *tan*. *Têng Yo* recommended him to the Emperor for the position of *t'ai-shou* of *Tung-kuan* 東官 (a *chün*, now Middle Kuangtung), but he declined again. Then *Têng Yo* appointed the son of his elder brother, *Ko Wang* 葛望 as *chi-shih-ts'an-chün* 記室參軍. In the mountain he led a happy and quiet life for many years, and wrote continuously . . .

19.) He called himself *Pao-p'u-tzŭ*, and gave this name also to his book. His other writings are: Inscriptions on Tombstones, Eulogies (on the dead, to be burnt at the grave), Poems, and *fu* 賦 (prose poems), one hundred *chüan* 卷; Official Correspondence between Equals, Despatches, and Memorials to the Throne, thirty *chüan;* Biographies of *shên* and *hsien*, of Good Civil Officers, and of Hermits, each ten *chüan;* further he copied the Five Canons, the *Shih chi* 史記 (Historical Records by *Ssŭ-ma Ch'ien* 司馬遷), the *Han shu* 漢書 (History of the Former Han Dynasty by *Pan Ku* 班固 and his sister), the writings of various philosophers and *fang ch'i* 方技 (that is, works on medicine, divination by tortoise shell, astrology, and physiognomy), and miscellaneous other things, three hundred and ten *chüan; Chin kuei yao fang* 金匱藥方 (Recipes to be kept in a Golden Coffer, that is, Valuable Recipes), one hundred *chüan;* and *Chou hou yao chi fang* 肘後要急方 (Recipes for Relieving Acute Diseases), four *chüan*. His wide learning could not be surpassed south of the Yangtze. His writings are more voluminous than those of *Pan Ku* and *Ssŭ-ma Ch'ien*. Moreover, they discuss clearly the depths of the mystery and give a reasoned account of the subtleties.

20.) Later on, he suddenly addressed a message to *Têng Yo* that he was obliged to go on a long journey in search of teachers and would leave shortly. Receiving the letter, *Têng Yo* made haste to pay him a farewell visit, but *Ko Hung* remained seated (did not rise to receive him). At noon, still in the same position, he died like one asleep. *Têng Yo* arrived, but did not succeed in seeing him. At that time he was eighty one years old (eighty in our reckoning). Although dead, his countenance looked alive and his body was limp. Upon being placed in the coffin, the body was very light like empty clothes. People said that he had achieved *hsien*-ship by means of *shih chieh* 尸解.[10]

AUTOBIOGRAPHICAL MATERIAL FROM OUTER CHAPTER L.

21.) When I was twenty and odd years old, I thought that the writing of short compositions only wasted energy and time. It was better for me to establish my own school; so I began to write a book on my philosophy *tzŭ-shu* 子書. At that time I became involved in military disturbances, and wandered homeless. Part of my book was lost. I left off writing for ten and odd years, for I was constantly on the road, until the era *Chien-wu* 建武 (317–317 A. D.) when I got it ready. I have written *Nei p'ien* 內篇 (Inner Chapters), twenty *chüan*, and *Wai p'ien* 外篇 (Outer Chapters), fifty *chüan* . . . Someone took exception to this writing of an autobiography saying: "You have just made a successful beginning to your official career; promotion is certain. Why do you write an autobiography, the work of an old man?"

22.) My nature is dull. I do not talk much. My appearance is ugly. These things cannot be disputed at all. As for my dress, my hat and shoes are dirty and worn, and my clothes sometimes ragged, but I am never ashamed of it. The style in others' clothes changes many times in a short period; sometimes, suddenly, it is a large collar and wide waistband, sometimes a narrow body and long sleeves, sometimes the skirts of a coat are so long that they trail on the ground and sometimes they are so short that they do not conceal the feet. But hoping to keep the old-established customs, I do not follow current changes. What I say is frank and true; I never engage in jest. If I do not meet a suitable man, I keep silent all day long. Therefore people all call me a *pao-p'u* scholar (i. e., one who keeps his basic nature, one who is unperturbed by the desires of the world). Accordingly I call myself so in the books which I write.

THE INNER CHAPTERS OF *Pao-p'u-tzŭ*.

Summaries, Extracts, and Translations.

Inner Chapter I. ON *Hsüan*

23.) *Hsüan* 玄 (the mystery) being the origin of nature 自然 is the ultimate source of the ten thousand differences.

24.) This chapter discusses the strange power of *hsüan* and the delightful life of a hermit.

Inner Chapter II. ON *Hsien*.

25.) Someone asks: Is it true that *shên* and *hsien* are immortal?

26.) *Pao-p'u-tzŭ* says: What one knows is not so much as what one does not know. There is a great variety of things. Since there are many *hsien* on record, why should there be no immortality?

27.) Someone says: There is living, there must also be dying—no matter whether one is a sage or a genius. It is better to do something easy and glorious, such as to engage in political affairs, than to sacrifice oneself by devotion to something impossible. This impossibility (longevity, immortality) will not be achieved even by *kuei* 鬼 and *shên* 神.

28.) *Pao-p'u-tzŭ* answers: There are many abnormal and extraordinary things not governed by ordinary rules. They can not be judged by common knowledge. Things in the universe are of unspecified variety. A man lives in the world, and yet he does not know what is over and under himself. How can the far-removed principles of *shên* and *hsien* be judged by common knowledge? *Hsien* do not live among people. Even if one passes through the world, he will conduct himself like a common person and will not be detected. A *hsien* can be detected only if he has a peculiar appearance. Since people slander them, the *chên-jên* 眞人 (true men, *hsien*) do not like it and conceal themselves more and more. But people believe that there are no *hsien* because they have never seen any. After observing that *Tso Tz'ŭ* 左慈 practiced abstinence from eating grains for about a month, and after seeing the magic of *Kan Shih* 甘始,[11] *Ts'ao Chih* 曹植[12] believed in *tao shu* 道術 (magic, alchemy?, etc.).

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[10] Cf. Henri Maspero, *Jour. Asiatique* **229** (1937) 178.

29.) *Liu Hsiang* 劉向 was a great scholar. He wrote the *Lieh hsien chuan* 列仙傳 (Biographies of the Immortals) which contains accounts of seventy and more *hsien*. So there must have been *hsien*. But it is regretful that people say that the book cannot wholly be trusted because the author was not a sage as were Confucius and others. People disbelieve in longevity because *Ch'in shih huang-ti* 秦始皇帝 (reigned 221–209 B. C.) and *Han Wu ti* 漢武帝 (reigned 140–87 B. C.) failed to achieve it, and because *Li Shao-chün* 李少君 and *Luan T'ai* 欒太,[13] devoted themselves to it without accomplishing anything. But we cannot say that longevity cannot be achieved because they failed. Furthermore, it is difficult to achieve *hsien*-ship. It is not certain that every learner will be successful, and the learning of *hsien* does not depend upon the learner being rich and powerful. The two emperors were busy with political and military affairs, lived with beautiful women, and enjoyed luxurious lives. They did not really learn *hsien*, and they did not meet *yu tao chih shih* ("alchemists") 有道之士 good at preparing *hsien* medicine, so they failed to achieve longevity. We common people on the other hand are poor and are worrying about earning a living. Perhaps we get the secret and meet an extraordinary teacher, but still we have affection for our families and will not leave them: and so death draws nearer and nearer. As to *Luan T'ai*, he was a mean man and dared to act falsely and extravagantly because *Han Wu ti* treated *fang shih* with too much favor. Although *Luan T'ai* was treacherous, this does not mean that there is no way of *hsien* . . . People do not believe in the existence of *kuei* and *shên*, but there are many records to prove their existence. The making of gold is described in the *Shên hsien chi* 神仙集 whence *Liu An* 劉安 (*Huai-nan tzŭ*) extracted the facts in his *Hung-pao chên chung shu* 鴻寶枕中書. An oral explanation, however, is needed to understand the text which is in code. *Liu Hsiang* failed to prepare gold from *Huai-nan tzŭ*'s prescriptions because he did not understand the secrecy of the recipe for preparing gold. But the *Lieh hsien chuan* which he wrote is based upon reliable sources: it is not false. People have only a little knowledge, how can they believe the superior principle?

Inner Chapter III. REPLIES TO A LAYMAN.

30.) Someone raises the objection: As pine and cypress (long-lived) among trees and as *Lao-tzŭ* 老子 and *P'êng Tsu* 彭祖 (men who lived long) among human beings are so endowed by nature, how may longevity like theirs be achieved by learning? *Pao-p'u-tzŭ* says: . . . The branches and leaves of pine and cypress are different from those of other trees . . . As to *Lao-tzŭ* and *P'êng Tsu*, they are not in a special category but are still merely human beings. They achieved longevity because of their achievement of *tao*, not because of nature . . . If a wise person devotes himself to the tao of *Lao-tzŭ* and *P'êng Tsu*, he will be as successful as they were.

31.) If one claims that there are no *hsien* in the world, there are, nevertheless, nearly one thousand *hsien* in the records of former authors. In the records their family names and sobriquets, and an account of their charitable acts are given. The records are therefore not false . . . but the *tao* of *hsien* is achieved slowly, and there are many taboos. A person cannot follow the rules and wait for the success of achievement unless he has an extraordinary will and determination. Some are suspicious and interrupt the learning of *hsien* at half way, and say that the *tao* of *hsien* and longevity is surely impossible of attainment . . .

32.) Someone says: Life and death as well as age are due to destiny, and cannot be affected by medicine. A finger may not be rejoined after being cut off. It is of no use to swallow the blood which has flowed out. How can the taking of pine and cypress which belong to another category prolong my short age? *Pao-p'u-tzŭ* says: . . . Water and earth are not of the same category with vegetables; the latter however live upon the former.[14] The five grains do not belong to the class of human beings but are vital for the latter . . . It is no wonder that the taking of those things which are suitable for the body and which increase the age will cause longevity!

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[11] The two were *fang shih* 方士 (magicians, alchemists?) summoned by *Ts'ao Ts'ao* who was a ruler *de facto* at the end of the later *Han* dynasty.

[12] Literatus of the end of the later *Han* and the beginning of the *Wei* 魏 dynasty, son of *Ts'ao Ts'ao*, founder of the *Wei* dynasty.

[13] *Fang shih* at the court of *Han Wu ti*, the first an honorable man and definitely an alchemist, i. e., a gold-maker, the second a dishonorable man. *Pao-p'u-tzŭ* in this chapter gives quotations, not here translated, to prove that *Li Shao Chün* did not die but became a *hsien*.

[14] The distinction here is between the vegetable and mineral kingdoms. Plants which are vegetable live upon water and earth which are mineral.

33.) The ancient records, in addition to describing about a thousand *hsien*, also describe birds, animals, trees, etc., of very long life. If one behaves in the way that these long-lived beings behave, he also will live long. But this is not necessary; many other ways to immortality are described in the books of *hsien*. Many mysterious actions of the ancients are recorded in history, and this proves that the actions occurred. Someone asks whether a man will be able to worship his ancestors if he becomes a *hsien*. *Pao-p'u-tzŭ* answers that *Lao-tzŭ* had a son, named *Tsung* 宗 who was a general under the *Wei* dynasty, so one can have sons if he is a *hsien*. A *hsien* may stay in the world or may rise to the heavens according to the different methods of taking the medicines. There are many things which are common, such as the practices of astrology, which cannot be understood by the common people, and it is so also with the *hsien* methods. One cannot become a *hsien* unless he has first accomplished many good deeds: Three hundred if one aims at terrestrial *hsien*-ship and twelve hundred for celestial *hsien*-ship, without interruption, for if the 1199th good deed is followed by a bad one, it will be necessary to recommence. And I suspect, says *Pao-p'u-tzŭ*, that *P'êng Tsu* did not mount to heaven because he lacked a sufficient number of good deeds.

Inner Chapter IV. ON THE GOLD (FLUID) AND (RETURNED) MEDICINE

34.) A complete translation of this chapter by *Wu Lu-ch'iang* with an Abstract Table of Contents has been published in *Proc. Amer. Acad. Arts and Sciences*, **70**, 234–255, 269-273 (1935).

Inner Chapter V. ULTIMATE PRINCIPLES

35.) Those who have achieved it (*hsien*) are scarce and unknown; those who have failed to achieve it are many and known. People cannot know the unknown, but see the known; therefore they say that there is surely no *tao* of *hsien* in the world! . . . The simple art of the physician is so wonderful, what cannot be accomplished by the *tao* of *shên hsien*! . . . *Pao-p'u-tzŭ* says: Although the taking of medicine is fundamental for longevity (immortality), yet its benefits are hastened if one can practice *hsing ch'i* 行氣 (the art of directing the movements of the ethereal essences in one's body) at the same time. Also, if he cannot procure medicine, but practices *hsing ch'i* only and understands its principle thoroughly, he will achieve an age of many hundreds of years. But he should also understand the art of *fang chung* 房中 (suitable sexual satisfaction), also known as the art of *yin-yang* 陰陽(之術).

36.) *Hsing ch'i* is also useful to protect against epidemics and against the attacks of spirits, tigers, snakes, and so forth, to stop the streaming of blood out of a wound, to make a river flow upwards, and for other extraordinary purposes.

Inner Chapter VI. CERTAIN SUBTLETIES

37.) After their achievement of *tao* (i. e. *hsien*), they rise to *ch'ing hsiao* 靑霄 (high in the sky) and ramble about *tzŭ chi* 紫極 (Palace of the Immortals). None will see and hear them except those who are able to communicate with spirits. Hence (the common people) still say that there are no *hsien*. It is not only now, but it has long been the case, that a man, believing in his speculation and own short (poor) opinion, considers that what he guesses is no error, accepts what is common and wonders at what is uncommon, and will not understand even if explanation is made to him thoroughly and with great effort.

38.) Although *Pao-p'u-tzŭ* is not yet a *hsien*, he will try to convince those who like the art and will not try to make everyone believe in it. The great medicine is difficult to prepare and is expensive. Lesser medicines ought to be prepared first for prolonging life, and one ought first to know how to enter a mountain without being attacked by fierce animals, to pass across a river without being killed by dragons, to protect oneself against epidemics, to disappear at once when in danger, etc. There are four ways for prolonging life, but they are not ways for *hsien*, namely, the art of *fang chung*, the art of directing the *ch'i* (ethereal essences), *tao-yin*, and the taking of common medicines. If a man devotes himself to the art of immortality, he should not do anything immoral, he should not kill even an insect, and he should do good deeds.

Inner Chapter VII. RESPONSE TO OBJECTIONS

39.) Someone says: Destiny bestowed by heaven should be impartial. Why is it that ordinary people like *Ch'ih-sung-tzŭ* 赤松子 and *Wang Ch'iao* 王喬 (two *hsien*) enjoyed longevity while the great *shêng* 聖, *Chou Kung* 周公 (the Duke of *Chou*) and Confucius, did not enjoy it?

40.) *Pao-p'u-tzŭ* says: Those whose fate belongs to the life-star will be sure to like the way of *hsien*. They will be sure to gain it if they seek after it. Those whose fate belongs to the death-star will be unable to believe in the way of *hsien* and naturally they will not devote themselves to it. So it depends upon his fate whether one will become a *hsien*, and it does not matter whether he is a *shêng* or a man of common knowledge.

41.) Someone raises the objection: Heaven has supernatural power. Why is not age extended by it?

42.) *Pao-p'u-tzŭ* answers: All things have their existence naturally. Each exists of itself, as heaven and earth exist. There is only the difference that some form earlier, some later, some have great volume, some small. Heaven and earth embrace all things, but all things are not created by them. Age does not depend upon heaven and earth. You think that heaven could not bestow longevity on Confucius and Mencius—which shows all the more clearly that fate is from nature and is not determined by heaven and earth. A worthy man does not necessarily die at an old age. A foolish person does not necessarily die young. Goodness is without immediate blessing. Evil is without immediate misfortune. Birth is without a fixed year. Death is not at a sure time.

43.) Someone says: Confucius says that from of old all have died. The Taoists say that *shên hsien* may be achieved by learning. The words of the sage are true and there is proof for them. The words of the Taoists are extravagant and hard to practise.

44.) *Pao-p'u-tzŭ* says: The teachings of Confucianism are near and easily applied. Therefore the teachings have many followers. The principles of Taoism are remote and difficult to understand. Hence there are only a few persons who understand them thoroughly. *Tao* is the source of all varieties. *Ju* (Confucianism) is the river of great purity. One should not esteem Confucius only and disregard Taoism. Confucius himself visited *Lao-tzŭ* and respected him very much.

45.) Confucius visited *Lao-tzŭ* personally; why did he not learn *tao* from him?

46.) *Pao-p'u-tzŭ* says: Confucius was busy propagating his own theory . . . Confucius was interested solely in the affairs of the common people and was not a person (suitable) for learning *hsien*.

47.) Someone says: Among the doings of the Confucianists and Taoists, what is difficult, what is easy?

48.) *Pao-p'u-tzŭ* answers: For the Confucianists the difficult is surrounded by the easy, while for the Taoists the easy is surrounded by the difficult.

49.) Someone says: The great scholars have never said that *hsien*-ship may be achieved. Yet you take as your support the way of longevity. I dare not believe it.

50.) *Pao-p'u-tzŭ* says: I believe it because, by examining its small evidences, I know its great efficacy. Seeing what has been done, I understand what has not yet been tested. People do not believe it because, by inference from what they have themselves experienced, they insist that there is no *shên hsien* which is a thing far away.

51.) *Pao-p'u-tzŭ* says: In ordinary matters every person has his likes and dislikes which are different from those of others. So also in the extraordinary matters of *shên hsien*, it is impossible to make everyone believe them. If I wait until the common people cease to slander (*shên hsien*), it will be as long as waiting for the clearing of the water of the Yellow River. I cannot keep silent, for I hope only to inspire those who may be persuaded. As to those who cannot be persuaded, even the ancients could do nothing with them!

52.) *Pao-p'u-tzŭ* says: It is not only now, but it has long been the case, that the superior principle has been difficult to understand and that *shên hsien* has not been believed. The best ones know them naturally. The next best apprehend them after being told. And everywhere there are persons who laugh a hearty laugh when they are told of these things! Even a sage or a genius can do nothing with them. They are hopeless!

Inner Chapter VIII

OVERCOMING OBSTRUCTIONS

53.) Someone asks: Human beings have many things to do, and to seek to become a *hsien* is very difficult. Unless something is neglected, the two cannot be prosecuted together. But how can the study of literature, our joys and sorrows, and political affairs be ignored?

54.) *Pao-p'u-tzŭ* answers: The search for *hsien*-ship is not complicated. Only a few things are to be done. The only concern is that the will is not steadfast and belief not confirmed. Why worry about the disregarding of human affairs? It is not difficult for the very competent to do the two things together. While treasuring in private the way of *yang shêng* 養生 in public he engages in world affairs. His person becomes very perfected because he controls himself. The state is at peace because he governs it. He teaches the six canons of Confucianism to ordinary folk, and the recipes to those who understand them. He stays in the world as a help to his generation, if he wishes to remain a while (in the world). If he wishes to mount (to *hsien*-ship), passing above the sky, he rises lightly. Such a person is of the first class. If a person knows that he has not enough ability for both, he disregards human affairs and devotes himself to *tao tê* 道德. Such a person is of the second class.

55.) Formerly *Huang-ti* 黃帝 ruled the world, but his political affairs did not prevent him from rising to heaven at *Ting Hu* 鼎湖. *P'êng Tsu* 彭祖 had been a *ta fu* 大夫 for eight hundred years before he went westward to the desert. *Po-yang* 伯陽[15] was a *chu shih* 柱史. *Ning Fêng* 甯封 was a *t'ao chêng* 陶正. *Fang Hui* 方回 was a *lü shih* 閭士. *Lü Wang* 呂望 was a *t'ai shih* 太師. *Ch'ou Shêng* 仇生 was an officer of the *Yin* 殷 dynasty (1401–1154 B. C.). *Ma Chou* 馬舟 was an officer of the *Chin* 晉 state. Having made *Yüeh* 越 a strong state, *Fan Li* 范蠡 traveled over the sea. *Ch'in Kao* was an officer of *Sung K'ang wang* 宋康王. *Ch'ang Shêng* 常生 lowered himself to be a groom. *Chuang Chou* 莊周[16] hid his talents as a subordinate officer. Many ancients saved the generation while attaining *tao*. They practised the *tao* amid political affairs, for they had a surplus of ability. Why must it be practised as a hermit? Why must worldly affairs be utterly abandoned to achieve it?

56.) But there are also those who liking tranquility and disliking noise take joy in living as hermits and dislike political positions. Dressing in poor clothes, they eat poor food and plow. Taking delight in their three reasons for joy, they maintain the norm and await the end. They do not contrive to prolong a useless life, and they do not fear sudden death. Declining presents of great value and foregoing official position, they pursue no (doctrine), but remain constantly as they are. How much the more surely would they not engage in public affairs, if they were made acquainted with the Way of the Immortals (*shên hsien*). But each of these groups (par. 55 and 56) is pursuing its will. They are not to be judged by one standard.

57.) *Pao-p'u-tzŭ* says: There is a proverb that a good maxim is more valuable than a thousand *liang* 兩 of silver. It applies, however, only to success or failure in military matters and in personal actions. As to telling others the secrets of longevity and the formulas of immortality, this is more valuable than the good advice of the ordinary man. If a person cures a patient who is at death's door, the patient will be deeply grateful to him. Today, according to the *Hsien ching* 仙經 (Book of Immortals), by rendering the nine-*tan* volatile and by preparing solutions from gold and jade, immortality can be conferred on the peoples of the world, not merely on a single person. How great was the virtue of *Huang-ti* and *Lao-tzŭ*! But out of ignorance to condemn it as a mythical account is regretful.

58.) *Pao-p'u-tzŭ* says: To become *shên hsien* one need only do the most essential things, namely *pao ching* 寶精, *hsing ch'i* 行氣 and take one great medicine. These are sufficient and not expensive.

59.) These three things, however, are characterized by both shallowness and profundity. You will not know all about them quickly unless you meet famous teachers and work extremely diligently. For *hsing ch'i* there are many processes, for *fang chung* 房中 nearly more than a hundred, for the medicine about one thousand formulas. Easy ones are taught to the student at first. If he is diligent, then the essentials will be given to him.

60.) Therefore, through *hsing ch'i* one may cure disease or live in the midst of epidemics, or exorcise snakes and tigers, or stop the streaming of blood out of a wound, or live under water, or walk on the surface of water, or be free from hunger and thirst, or prolong one's span of life. Its main point is *t'ai hsi* 胎息 (to breathe like an embryo). Those who achieve *t'ai hsi* can breathe without using nose and mouth, as in a pregnant womb. When this happens, the *tao* is achieved.

61.) To begin to learn *hsing ch'i*, one inhales air through the nose and holds it while he counts in silence to one hundred and twenty; then the air is exhaled gently through the mouth. The inhalation and exhalation should be so gentle that one does not hear the sound of the breath oneself. The inhaled air is retained so that it amounts to more than that which is exhaled. The breathing should be so gentle that a little feather put before the nose is not disturbed during the exhalation. The numbers which one counts while holding the inhaled air are increased gradually. Finally the number can be increased to one thousand. Under these conditions, one day at a time, an old man will change into a younger.

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[15] *Lao-tzŭ* is evidently intended here, not *Wei Po-yang* 魏伯陽 the alchemist. ch. *Isis*, **18**, 210 ff. (1932). According to the *Tz'ŭ Yüan* 辭源., the *tzŭ* of *Lao-tzŭ* was *Po-Yang*. According to *Ssŭ-Ma Ch'ien*, *Lao-tzŭ* was a *chu shih*. There is no record that *Wei Po-Yang* was a *chu shih*.

[16] i. e. *Chuang-tzŭ*.

62.) *Hsing ch'i* should be practiced at the *shih* 時 (hours) of life-*ch'i* not at the *shih* of the death-*ch'i*. The old saying, a *hsien* takes six *ch'i*, is a reference to this. There are twelve *shih* for one day and one night. The *shih* from midnight to the noon of the next day are the *shih* of the life-*ch'i*. The *shih* from noon to midnight are the *shih* of the death-*ch'i*. It is not profitable to practice *hsing ch'i* during the *shih* of the death-*ch'i*.

63.) If an expert in *hsing ch'i* blows on water, the water will flow in the opposite direction for many *pu* 步 (steps); if on a fire, it will be extinguished; if on a tiger or a wolf, the animal will be unable to stand; and if on snakes, they coil up and cannot escape. If another person is wounded by a sword, the blood will stop streaming out if he blows upon the wound. If he hears that someone has been stung by a poisonous insect, he can cure in absentia the person who has been stung by blowing on his own hand and praying. If the person is male, he blows on his left hand; if female, on his right. Although the person who was stung is far away from him, yet he is cured at once. *Chung O* 中惡 (an illness producing sudden death) or an acute disease will be cured at once if the diseased person swallows the *ch'i* of Three-Nine. But hurry is a characteristic of most human beings, and only a few of them can maintain tranquillity in order to practice such a *tao*.

64.) Again, it is important in practicing *hsing ch'i* that one should not eat too much. When one eats uncooked vegetables and fatty and fresh foods, the *ch'i* becomes strong and is retained with difficulty. Anger should be forbidden, for the *ch'i* is disturbed if one is often angry, and the *ch'i* cannot flow freely. Sometimes it causes coughing. Consequently, only a few are able to practice *hsing ch'i*.

65.) My great uncle *Hsien-kung*, when very drunk or during very hot summer weather, would go to the bottom of a deep pool and stay there for almost a day, simply because he was able to keep the *ch'i* and to breathe like an embryo.

66.) There are more than ten schools for the art of *fang chung*. Some are for repairing weakness, some for curing diseases, some for increasing *yang* by taking from *yin*, and some are for prolonging life. The most important thing is to return the sperm to repair the brain. This method is handed down by *chên jên* 眞人 (true men, the accomplished) only by oral teaching. It has not been written down in a book. Even though famous medicine is taken, while this important method is not understood, longevity will still not be achieved.

67.) The human desire may not be completely abandoned. The "stoppage-sickness" will be induced if sexual satisfaction is lacking. Therefore those who are in prison and do not marry are often sick and do not attain old age. On the other hand, sexual indulgence shortens life. Only by controlled satisfaction is there no impairment. One may destroy his health by practicing the art of *fang chung* without getting the secrets. *Hsüan-tu su-tzŭ* 玄都素子, *Jung-ch'êng kung* 容成公 and *P'êng Tsu* wrote only the general method; by no means did they commit the important methods to paper. Those who look eagerly for immortality should seek the methods with diligence. I obtained the information from my teacher *Chêng chün*. Therefore I write it down for the *tao*-believer of the future. This account is not a product of my imagination. But I have not really learned all of the secrets. Some *tao shih* 道士 (Taoist priests, Seekers of the Way) devote themselves only to the art of sexual intercourse for achieving *shên hsien*, without preparing the great *chin* and *tan* medicines. This is the pinnacle of ignorance.

68.) *Pao-p'u-tzŭ* says: Only a few *tao shu* 道書 (books of *tao* or canons of taoism) are from *Huang Ti* and *Lao-tzŭ*. Most of them are from later lovers of the marvelous who wrote down an augmented account of what they knew and saw. These are now very voluminous. The ancients were plain folk and mostly not geniuses. Their discussions on the principle of nature are not detailed. Their proofs are not clear. They all omitted the important points, and are difficult to understand. Even an understanding of them does not lead far. They are not sufficient for explaining subtleties, for convincing doubters, for inspiring those possessed of resolution, and for teaching beginners so that they know the way of the Mystery and the sources of blessing and distress. Even if they are read over and over, nothing may be obtained from them. Even if one wishes to read much, good books should be selected and then attention should be paid to them. *Tao shu* of no importance are not worthy of study. Inferior students do not always distinguish whether the authors are good or not. They copy all the books which belong to the school of *tao*, then study diligently these many books. They are like those who seek in the nest of a swallow for the egg of a phoenix, and fish for eels at the bottom of a well. No matter how diligent they are, they do not find them. They attain nothing practical. Fruitlessly they waste days and months. They have nothing for their pains. There is not the slightest advantage. On the one hand they neglect the affairs of the present world, and on the other they do not achieve immortality. Everyone points to them and says that they study so diligently, but they cannot achieve immortality, and therefore there is really no method of immortality in the world; but those who point to them do not know that their method of seeking *hsien*-ship is like that of a person who stands by a river and wishes to catch fish, but has no net. It is not that there are no fish in the river.

69.) Furthermore, although the Book of Five Thousand Characters[17] is from *Lao-tzŭ*, yet it discusses only general ideas. There is nothing in it which is completely and concretely stated. It is vain to repeat this canon from memory without obtaining the essentials. Books inferior to it are even worse. As to *Wên-tzŭ* 文子, *Chuang-tzŭ* and *Kuan-ling Yin Hsi* 關令尹喜,[18] although their writings are based upon the principles and Mystic Void (*Hsüan Hsü*) 玄虛 of *Huang Ti* and *Lao-tzŭ*, yet only the general content is described; the final word is not there at all. Sometimes they equalize death and life, saying there is no difference. They consider life as hard labor and death as rest. They are millions of miles away from *shên*- and *hsien*-ship. They are not worth bothering with. Their allegories and similes may be so used that sharp-tongued and loose-lived fellows of an evil epoch can take *Lao-tzŭ* and *Chuang-tzŭ* as the sources for cunning arguments. How regretful it is!

70.) Someone says: Under a good ruler only good persons are valued. But persons devoting themselves to *hsien*-ship should not be made officers. If all pursued the *tao* who would help the ruler to govern the state?

71.) *Pao-p'u-tzŭ* says: *Ch'ao Fu* 巢父 and *Hsü Yu* 許由 are considered to be noble, for they left good rulers and lived in mountains. *Chuang Po* 莊伯 has a good reputation, for he left a good ruler and lived the life of a hermit. When *Hsien-yüan* 軒轅 (i. e. *Huang-ti*) ruled the world very well, *Kuang-ch'êng-tzŭ* 廣成子 was a hermit. When *T'ang Yao* 唐堯 ruled the world, it was very tranquil, but *Wu Ch'üan* 偓佺 was not his officer. But good government was not impaired; able men were not lacking because of his absence. When *T'ien I* 天乙 revolted, *Wu Kuang* 務光 carried a stone and jumped into the *Ho* 河 (Yellow River). After *Chi Wu* 姬武[19] had overthrown the *Shang* 商 dynasty, *Po I* 伯夷 and *Shu Ch'i* 叔齊 went without food in West Mountain. During the rise of *Ch'i Huan kung* 齊桓公, *Shao Chi* 少稷 stayed in a poor street. During the rise of *Wei Wên hou* 魏文侯, *Tuan Kan Mu* 段干木 lived at West River 西河 with dishevelled hair. The Four Elders[20] lived as hermits in *Shang Lo* 商洛 mountain, but the procuring of officers for the great *Han* dynasty was not hindered. *Chou Tang* 周黨 lived in retirement, but the peaceful rule without punishment of *Hsiao Wên* 孝文 (reigned 179–156 B. C.) was not diminished. In a thousand years there are some whose minds cannot be excited by the favor of an emperor, whose desires cannot be changed by the utmost riches, who keep their lofty virtue, who do not crouch and are not disgraced, and who enjoy a rural quiet and poor life as if it were the life of the rich and the pomp of power! There will be still fewer who, leaving their families and relatives, enjoy a life of solitude and purity in famous mountains! Are you not worrying too much that the sovereign will have no officials?

72.) Somebody says: Those who learn *hsien* keep themselves noble, but forget the disturbing of human relationships. They leave their rulers, and are insolent in their failure to be good subjects. I fear that they will suffer punishment before they attain longevity.

73.) *Pao-p'u-tzŭ* answers: *Pei Jên Shih Hu* 北人石戶, *Shan Chüan* 善卷 and *Tzŭ Chou* 子州 were all geniuses, but were recluse hermits. They had no bad influence on politics. Those who learn *hsien* are not necessarily men of political ability. It makes no differences to a government whether they hold offices under it or not.

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[17] i. e. the *Tao tê ching* 道德經. （道德五千言）.

[18] *Kuan-ling* means the magistrate of the Pass (through which *Lao-Tzŭ* traveled westward).

[19] *Wu Wang* 武王 of the *Chou* 周 dynasty (1122–255 B. C.).

[20] Namely, *Tung Yüan kung* 東園公, *Ch'i Li Chi* 綺里季, *Hsia Huang kung* 夏黃公, and *Lu Li Hsien-shêng* 角里先生.

74.) China is now under one rule. People come even from the frontier regions as officers. Many able men cannot get positions. People are obliged to wait for positions; there are no vacancies in government offices even for a short time. Those who have served diligently for a long time must still wait to be raised to higher offices. There have never been so many people of these kinds. No one is sought after.

75.) Formerly the Heir Apparent, *Chin* 晉, left his father and set aside the inheritance of the crown, but *Ling wang* 靈王[21] did not blame him for filial impiety. *Yin Shêng* 尹生 left his office, but the government of the *Chou* dynasty did not punish him for disloyalty. It was understood that they had other inclinations and were men of iron will.

76.) A good ruler understands that each person has his own nature. He shows his clemency by leaving his subjects free. The sovereign is not biased by envy, and his subjects are overjoyed with satisfaction. In consequence his good reputation spreads far and wide, and covetous men blush to hear of it.

77.) I have heard that furs and stoves are discarded when the weather turns warm, and that men of talent retire from office when the world is at peace. When the Empire was at peace again, *Chang Liang* 張良, *Han Hsin* 韓信 and *Ying Pu* 英布 retired from the active lives of military adviser and of generals respectively. How much the less will a government ever retain in its service people who are learning *hsien*-ship! These people make it their business to have few thoughts and few desires. Their object is to preserve their bodies from harm and to secure longevity. They do no disgraceful deeds, such as to struggle for place. They offer no challenge to popular prejudices. What then is their crime? Furthermore, the grandeur of a large mountain is not modified by putting on it or taking away from it a little bit of earth, nor that of an ocean by pouring into it or out of it a spoonful of water. There are only a few *hsien* in one generation. How can the number of the officials be diminished thereby?

78.) Somebody says: If *hsien tao* 仙道 (way to *hsien*) may be really achieved, then why is there no record of it in the Five Canonical Books? Why did not *Chou kung* 周公 and Confucius speak about it? Why were not the *shêng* immortal? And why did not the geniuses live forever? If *Chou kung* and Confucius did not know it, they may not be considered as *shêng*. If they knew it and did not learn it, there is no *hsien tao*.

79.) *Pao-p'u-tzŭ* answers: Everyone is born under a certain star, as detailed in a preceding chapter. You are like the person who looks up to the heavens with a basin over his head so that he does not perceive the brilliance of the Seven Brightnesses,[22] and like the one who looks at a great river for a short time and so does not know the marvels of its depths. There are endless things which were not recorded in the Five Canonical Books, and were not mentioned by *Chou kung* and Confucius. I will tell you about a minute fraction of them. I will give you a glimpse of them, although it is difficult to explain to you clearly. The *I Ching* 易經 (Book of Changes) was completed by nine *shêng*, and is sufficient for ordering *Yin* 陰 and *Yang* 陽 so that nothing can be added. Today, if you ask an expert on *I Ching:* how many degrees there are around the whole of heaven; the area of the Four Seas; the dimensions of the universe; the limit above; the base beneath; who causes the revolution; why the sun revolves slowly while the moon revolves quickly; if you inquire of him concerning the Nine Paths (of the moon); the variation in the lengths of day and night; the alternations among the Seven Stars; the waxing and waning of the five planets; *Kuan* 冠, *Êrh* 珥,[23] light impairment, and eclipse; the impingements on the Four and the Seven; whence come *Sê* 彗 (a comet) and *Po* 孛; the uncanniness of *Ch'i* 氣 and *Shih* 矢 and the good omen in *Ching* 景 (a star) and *Lao* 老; why are *Chên* 鎮 (a star) and *Chi* 極 (a star) stationary; why *Chên* 鎮 (Saturn) is found only in the east; why the weather is hot when *Hsi Ho* 羲和 (the charioteer of the sun) exteriorizes light and cold when *Wang Shu* 望舒 (the charioteer of the moon) turns the mirror inward; why the weather will be moist if the Milky Way is up; why tides are sometimes high and sometimes low; why joy and anger are expressed by music; why the floating of clouds and the coming up of *ch'i* 氣 (atmosphere or mist) are omens foreshadowing good or evil; why some of the following-named are successful with *shih* 亓 while some fail with *chêng* 正—*T'ien Ch'an* 天欃

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[21] A king of the *Chou* dynasty. He reigned from 571–543 B. C.

[22] The sun, the moon and the five planets.

[23] Two kinds of astronomical phenomena similar to halo.

T'ien Ch'iang 天槍, *Ch'ih Yu* 蚩尤, *Wang Shih* 枉矢 (an evil star), *Hsün Shih* 旬始, *Ko Tsê* 格澤 (a lucky star), *Ssŭ Chên* 四鎮 (a star), *Wu Ts'an* 五殘, *T'ien Kou* 天狗 (a star in Argo) and *Kuei Hsieh* 歸邪 (an evil star)—he cannot answer and explain them. If you ask, in order, experts in the Spring and Autumn Classic, the *Ssŭ Pu* 四部, the Book of Poetry, the Book of History, and the Three Rites, none of them can answer your questions. All will answer: "All these subjects are not recorded in the orthodox canons. They are recorded in detail only by *Wu Hsien* 巫咸, *Kan kung* 甘公, *Kan Tê* 甘德, *Shih Shên* 石申, in the *Hai chung hsing chan* 海中星占 (an astrological book), by *Ch'ih Mêng* 郗萌, and in the *Ch'i yao lun* 七曜論." Then I shall ask them: "Are the books of the six experts canonical?" They will say: "No." Then I shall ask again: "Are *Kan Tê* and *Shih Shên* saints?" They will also say: "No." Then human beings have spent their whole lives with the heavens above and the earth beneath them, but information about them cannot be found in the Five Canonical Books or in the books of *Chou kung* and Confucius. May all of the (additional information) then be considered as false? The heaven and the earth are very large. Even the things which we see can not be understood. How can things which are very mysterious be understood? If you ask ordinary persons about a thousand such strange things as (the following):[24] the country where one rides clouds and is born from a cocoon; the people whose livers and hearts never deteriorate; the nest-dwellers and the cave-dwellers; those with one eye and three heads; those with horse- and dog-feet; those with long legs and crossed thighs; *Huang ch'ih* (place name) 黃池 without males; those with pierced breasts (through which a pole is passed for their transportation) and mouths to the side; if one lifts a stone at *Lin-chün* 廩 earth-boats float; if one strikes a tree at *Sha-i* 沙壹 dragons come forth; the land of *Nü-kua* 女媧 produces cuckoos; heaven drops large bricks; the flying dog speaks; the mountain shifted and the altar to earth moved; in one morning the three armies were transformed; the *chün-tzŭ* became cranes and the *hsiao-jên* became sand; a woman of normal size leans against a dead tree; 貳負抱桎; the insects in the dwelling; 委甲步肉; the two-headed snake was used as a bow-string; the wood that did not turn to ashes; the fire that was not hot; the bird of *Ch'ang-shu* 昌蜀; the eyeless animal; the head without a body; the headless body; the *ching-wei* 精衞 (name of a bird) fills the sea (with its song); the *chiao-jang* 交讓 (an evergreen) is born again and again; the cloth which is washed in fire; the jade-cutting knife; *Yen-mei* 炎昧 spits fire; *Mo-ni* 磨泥 sweats water; the grove of dead trees changed its form; the mountain-*k'uei* 夔 (a fabulous animal) has its heels in front; the nine heads of *Shih-hsiu* 石脩; the human face of the *pi-fang* 畢方 (fabulous bird); when *Shao-kan* 少干 brought accusation against *Po-shuai* 伯率; when the Saint's minister used *Su-shuang* 肅霜 (a thoroughbred horse) at hard labor; the Western *Ch'iang* 羌 owe their rise to *T'ang Ching* 唐景; the *Hsien-pi* 鮮卑 are strong because they ride *pieh* 鼈; *Lin-i* 林邑 made *Shên-lu* 神錄 king; *Yung* and *Shu* 庸蜀 made *Liu-shih* 流尸 emperor; when the child picked up the salt-god, a bug flew away; *Ts'ung-mu* 縱目 appears every generation in *Ching-hsiu* 荆岫; *Wu-ting* 五丁 brought the snakes to *Ch'ing-hsün* 傾峻; *Jou-shên* 肉甚 beats his fins at *San-hai* 三海; the jade characters on the gold plaque appeared from the side of *Yü's* 禹 well (禹穴); the horizontal lever on the vertical contrivance was cut from *ho-shih* 合石;—these have not been recorded in the Five Canonical Books, and have not been described by *Chou kung* and Confucius, —they will all say that there were no such things? As for the Southerners who can simply insert a pole (through the breast) for their transportation; the guardsman who shot his arrow while stationed at *Chou-shui* 肘水;[25] *Po-hun* 伯昏 balanced himself back and forth as he trod *I-jên* 億仞 under foot; *Lü-liang* 呂梁 could sing to calm its pools; the Duke of *Sung* overcame *Hsiang-yeh* 象葉 by confusing the truth; *Kung-shu pan* 公輸般 flew a kite of wood; *Li Chu* 離朱 could see a hair at a hundred paces; *Pên Huo* 賁獲 applied his strength to lifting fifteen tons; the man of *Yüeh* 越 resuscitated the dead with the prick of a needle; *Shu Hai's* 竪亥 stride covered thousands of feet; the man of *Ying* 郢 brandished his axe at *Pi-o* 鼻堊; *Chung-Tu* 仲都 bared his body in the winter;—all of these things could not be done by *Chou kung* and Confucius. May they also be considered as non-existent?

80.) If there was truly something which could not be done by *shêng*, then it is not strange that they did not achieve *hsien*-ship. Even if they did not achieve *hsien*-ship, they were still *shêng*. That by any chance *shêng* were not familiar with certain matters, this is no reason to attack them.

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[24] The lists of mirabilia are translated with all reserves.

[25] This list of mirabilia is translated with all reserves.

The *shêng* could sometimes treat with equanimity both their remaining in office and their quitting it. From nature possessed of bodies, they did not consider them their own. They lived, but they gave no thought to life or death. They abided by the long or short mandate from Heaven. Therefore, it is no wonder that they did not study for *hsien*-ship.

Inner Chapter IX. THE MEANING OF *tao*.

81.) The metaphysical aspects of *tao* are described. Worldly pleasures shorten human life; we ought to discard them, otherwise even worship is without effect; *Pao-p'u-tzŭ* discredits the worship of miscellaneous gods to which common people resort in order to obtain blessings or to cure disease. If one takes care of his health by avoiding worldly pleasures, even if he disregards the worship of miscellaneous gods, he will still live long. Evil *tao-shih* are described who cheat people by pretending to be immortal, while in truth they can do nothing extraordinary and know nothing about *hsien*. Various superstitions of common people are described which are really nonsense. People who know nothing about the art of *hsien* but who attain old age are very rare. They would have died at a younger age if they had been exposed to danger or to epidemics. Their old age is due to their good luck.

Inner Chapter X. EXPLANATION OF THE FUNDAMENTAL.

82.) Someone asks: Formerly the *chên jên*, *Ch'ih Sung-tzŭ*, *Wang Ch'iao*, *Ch'in Kao* 琴高, *Lao-tzŭ*, *P'êng Tsu*, *Wu Ch'êng* 務成, and *Yü Hua* 鬱華 were all officers in the world, and did not in those early times live as remote hermits. But why is it that, since the middle period,[26] the people who are devoted to *tao* are all hermits?

83.) *Pao-p'u-tzŭ* answers: In ancient times the people were honest; cunning and guile had not yet appeared. Those who believed in *tao* studied it diligently. Those who did not believe in it also kept silent and had no slanderous speech or opinion. Therefore *chên-jên* stayed in the world and did not hurry to ascend to the far-off (as *hsien*). Nowadays the world is morally depraved and imbibes deeply of cunning and hypocrisy. Honesty falls into decay while vice prevails. People not only do not believe in *tao*, but also they like to assert slanderously that *shên* and *hsien* are false and that they agitate or beguile the masses. Therefore, the superior 上士 (*hsien*) is ashamed to live in society.

84.) *Taoism* is better than Confucianism; indeed, *Pao-p'u-tzŭ* says, it is out of *Taoism* that Confucianism developed. *Tao* functions everywhere without hindrance (like *hsüan* of Inner Chapter I). Disregard of *tao* brings about distress . . . After people have achieved the *hsien* medicine, they can stay in the world as long as they wish, for no one then can do any harm to them. Confucianists serve the human world; *Taoists* are usually hermits. *Taoists*, however, can also serve the world first and afterwards devote themselves to the art of *hsien*. People like to discredit the *Taoists* because they are themselves too mean to study *hsien*.

Inner Chapter XI. ON HSIEN MEDICINES.

85.) *Pao-p'u-tzŭ* says: *Shên Nung*[27] *ssŭ ching* 神農四經 says: The superior medicine preserves the body from harm and prolongs life, so that the eater will rise up to become a *shên* 神 of the heaven, and roaming upward and downward (between the heaven and the earth) will control the numerous spirits. Hair and feathers will grow on his body, and food will appear instantly upon demand. It further says: "As for taking the five *chih* 芝, cinnabar, *yü cha* 玉札, *tsêng ch'ing* 曾青, realgar, orpiment, mica, and *t'ai i yü yü liang* 太乙禹餘糧—any one of these—the eater will be able to fly and to live long." And: "The middling medicine fosters our nature 性. An inferior medicine cures disease. It prevents the eater from being stung by poisonous insects, from being attacked by fierce animals, from being infected by epidemics, and it wards off all evil spirits." *Hsiao ching yüan shên ch'i* 孝經援神契 says: "Pepper (cayenne pepper) and ginger protect the eater from dampness, calamus (*Acornus calamus*) increases the ability to hear, sesame prolongs life, and *wei hsi* 威喜 protects the eater against weapons." All these are the best statements of superior *shêng* and the true record of *fang shu* (recipes). They are evident, but still people do not believe them. How regretful it is!

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[26] This is probably to be equated with the Buddhist middle period of the Doctrine, i. e. the present when we possess only a likeness of the original good and perfect Law.

[27] *Shên Nung*, 神農 the legendary Emperor, B. C. 2838, who is supposed to have invented agriculture and medicine.

86.) The best *hsien* medicine is cinnabar. Others in the order of decreasing excellence are gold, silver, *chih*, the five jades, mica, pearl, realgar, *t'ai i yü yü liang*, *shih chung huang tzŭ* 石中黃子 (literally yellow nucleus in stone), *shih kuei* 石桂 (stony cinnamon), quartz, *shih nao* 石腦, *shih liu huang* 石硫黃 (a kind of raw sulfur), wild honey and *tsêng ch'ing*. The last ones (of the *hsien* medicines) are resin from pine and cypress, *Panchyma cocos* Fries 茯苓, *Rehmannia glutinosa* Lib. 地黃, *Ophiopogon spicatus* Gawl. 麥門冬, *mu chü shêng* 木巨勝, *chung lou* 重樓, *Coptis teeta* Wall 黃連, *Polypodium lingua* Sw. 石韋, the berry (seed) of *Broussonetia papyrifera* Vent. 楮實, *hsiang ch'ia* 象柴 the other names of which are *shun lu* 純盧, the stick 杖 of *hsien*, or the stick of *Hsi Wang Mu*, 西王母[28] or *t'ien ching* 天精, away from oldness 却老, the bone of the earth 地骨, and *kou ch'i* 苟杞 (*Lycium chinense* Mill.).

87.) *T'ien mên tung* 天門冬 (*Asparagus lucidus* Lol.), the other names of which are *ti mên tung* 地門冬, *yen mên tung* 莚門冬, *tien chi* 顚棘, *yin yang shih* 淫羊食, and *kuan sung* 管松, occurs in high places. That which has a short root, tastes sweet, and is odorous, is good. That which occurs in the lowlands beside water, with leaves as fine as *yün* 蘊 (an aquatic grass), yellowish, with a long root, which tastes bitter and has a bad odor, is inferior. It may also be taken. But it readily causes belching, and its effect is slow. After it has been taken for one hundred days, the eater will be much stronger than after taking *shu* or *huang ching* 黃精. After entering a mountain, one may steam it. If it is taken after cooking, it will enable one to dispense with cereals if enough is taken. After the eater has become strong, he may lick it. It may also be pulverized. It is much better if the powder is taken with liquor made of the sap squeezed out from it. *T'ien mên tung* is called *pai pu* 百部 by the natives of *Ch'u* 楚. But they have a grass *pai pu* (*Stemone tuberosa* Lour.) whose root consisting of more than one hundred pieces completely resembles *t'ien mên tung*. But its sprout is somewhat different. The sprout of true *pai pu* is like *Smilax China* L. 拔楔, and may only be used to cure cough and as an insecticide for lice. It may not be used for *fu shih* 服食[29] and must not be used by mistake (in place of true *t'ien mên tung*). *Huang ching* also, for example, is called *pai chi* 白及. But in truth it is not the *pai chi* suitable for making paste. Many medicines of the *Pên ts'ao* 本草 have the same names as other grasses. Only experts can distinguish them. Attention should be paid to this point.

88.) *Huang ching* is also called *t'u chu* 兎竹, *chiu ch'iung* 救窮 and *ch'ui chu* 垂珠. To take its flower is better than to take its seed. To take its seed is better than to take its root. But it is difficult to get a sufficiency of its flower. Ten *hu* 斛[30] of the fresh flowers after drying amount to only five or six *tou* 斗. But it is taken in doses of three *ko* 合 daily. Only persons of great wealth can get such a quantity of it. If *huang ching* is taken for only ten years, its benefits already will have been very much enjoyed. But it is not as good as *shu* for relieving one from eating cereals. After taking *shu*, the eater will be corpulent and strong, will be able to carry a heavy load and to get over dangerous places. It is, however, not as sweet and delicious and easily edible as *huang ching*. During a year when the harvest is poor, it may be used as a substitute food for old and young. People cannot distinguish it from rice and consider it to be dried rice-cake.

89.) The five *chih* 芝 are stone *chih*, wood *chih*, grass *chih*, flesh *chih* and mushroom *chih*. There are more than a hundred varieties of each.

90.) Stone *chih*: Stony elephant *chih* occurs on famous mountains which are situated on the seacoast, and on the rocky sea-coast of islands. That which is like a fleshy elephant, with a head, a tail and four feet, is very similar to a living elephant. It adheres to a large stone, often on a high cliff or steep place. Some creep up and down. A red one is like coral, a white one is like fat cut into pieces, a black one is like *tsê chi* 擇漆 (a certain grass), a green one is like the feathers of a hen kingfisher and a yellow one is like red gold. All are as bright and transparent as hard ice. On a dark night we see their light when we are three hundred paces distant from them. A large one weighs more than ten *chin* 斤,[31] and a small one three or four *chin*. They cannot be discovered by a person who has not fasted long and most diligently and who does not carry *Lao-*

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[28] A female fairy the stories concerning whom prevailed only in ancient China.

[29] The taking of a medicine for procuring longevity.

[30] A grain or liquid measure. One *hu* = 5 *tou* = 50 *shêng* 升 = 500 *ko*. One *shêng* at present equals 1.0354688 liters.

[31] One *chin* = 16 *liang*. One *liang* at present equals 37.301 grams, but the ancient system was somewhat different.

tzŭ ju shan ling pao wu fu 老子入山靈寶五符[32] (The Five *Ling Pao* Charms of *Lao-tzŭ* for Entering a Mountain). When the *chih* are discovered, *K'ai shan ch'io hai fu* 開山却害符 (the Charm for Opening a Mountain and warding off injury) is put upon them; then they cannot disappear. Later on, the day of *Wang Hsiang* 王相 is chosen for gathering the *chih,* with praying, after a *chiao* 醮 (religious service, usually Taoistic) has been performed in which wine and dry meat are sacrificed to the *chih.* The persons who gather the *chih* all go to fetch them in the broad sunlight with *yü pu* 禹步 (shuffling gait) and with held breath. If the stony elephant *chih* is obtained, it is pounded thirty-six thousand blows with a pestle. One *fang ts'un pi* 方寸匕 (i.e. one square inch spoonful) is taken three times daily.[33] After one *chin* is taken, an age of one thousand years will be achieved; after ten *chin,* then an age of ten thousand years. The pills may also be given to other persons, so that persons other (than those who have gathered the drug) can take them also.

91.) Jade-fat *chih* occurs in the mountains which produce jade, in steep places. The grease of jade flows out and freezes forming *chih* after more than ten thousand years. Some jade-fat *chih* has the shape of a bird or of an animal. Its color varies; oftentimes it is similar to black mountain and deep-green water jade. It is also transparent as rock crystal. It is obtained and pulverized, and on mixing with the sap of *Wu hsin ts'ao* 無心草 it forms a solution at once. When one *shêng* of the solution is taken, an age of one thousand years will be achieved.

92.) Seven-*ming* 明 and nine-*kuang* 光 *chih* are all stones. They occur in stony cliffs of high mountains overlooking the water. Their shape is like that of a plate or a bowl with a diameter of only one *ch'ih* 尺 with stalks and petioles, and three or four *ts'un* high. Those with seven holes are called seven-*ming* (bright); those with nine holes nine-*kuang* (light). Their lights are like those of the stars. Within a distance of more than one hundred paces their lights are visible at night. Their lights are different and may be scattered, but may not be united. They are sought at the time of the autumnal equinox. They are obtained and are pounded, and then are taken. After a *fang ts'un pi* is taken into the mouth, then one feels somewhat warm and perceives that it tastes delicious and sweet. After one *chin* is taken, an age of one thousand years is achieved. They cause the body of the eater to be bright. The dark place where he lives is as bright as a moon, and objects can be seen there at night.

93.) Wild honey *chih* occurs in the stony door of Mt. *Shao-shih* 少室 (in *Têng-fêng* 登封 District, *Ho-nan* 河南 Province). At the door there is a deep valley which cannot be passed over. If one throws a stone into it, the echo is still heard after half a day. More than ten *chang* 丈 out from the door there is a stone column. Over the column there is a *yen-kai* 偃蓋 stone which is over a *chang* high and over a *chang* in diameter. The honey *chih* seems to extend from the stone door into the *yen-kai.* At long intervals there is a drop like rain: the remaining drops in the back of the room fall one at a time. Nevertheless, though the honey *chih* flows without cease, the *yen-kai* does not overflow. Above the door, a *k'o tou* 科斗 (tadpole characters) inscription is inscribed on the stone: "Those who are able to take one *tou* of wild honey *chih* will enjoy an age of ten thousand years." *Tao shih* all think about the place but they cannot approach it. However, they often try to collect the honey *chih* by means of a bowl attached to the end of a strong stick of bamboo or wood. But there has never been any success. The inscription on the stone door being as it is, there must have been someone who formerly got the *chih.*

94.) Stony cinnamon *chih* occurs in stony caves of famous mountains. It is like a cinnamon tree, but is really a stone. It is more than one *ch'ih* high; the greatest diameter is a *ch'ih.* It is transparent and tastes acrid. Its branches are taken after having been pounded. An age of a thousand years will be achieved if one *chin* of it is taken.

95.) *Shih chung huang tzŭ* occurs everywhere, most abundantly at Mt. *Ch'in shui* 沁水. A large stone which contains it is always moist and not dry. It is obtained by beating away tens of layers of the outer crust of the stone. In a large stone, it is reddish yellow and liquid like an egg in its shell. It should be drunk at once otherwise it will freeze into a stone, and it will be impossible to take it. As for a reasonable procedure: Before it hardens, drink it; once it has hardened, it will be necessary to grind it in order to take it. The largest amount obtainable by breaking one piece of stone is one *shêng*, the smallest about several *ko*. It can be taken all at one time. If only a little can be obtained at one time, it is taken continuously. If the amounts altogether total three *shêng*, then an age of one thousand years will be achieved. More may be taken, but the difficulty of getting it is considerable.

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[32] *Ling Pao,* one of the three supreme Gods of Taoism.

[33] According to the *Pên ts'ao kang mu* 本草綱目 a *fang ts'un pi* is a spoon one square *ts'un* 寸 in size with which powders are measured until it is just full. For pills or powder, a *tao kuei* 刀圭 is equal to one tenth of a *fang ts'un pi,* and is as much as ten seeds of *Sterculia platanifolia* Linn.

96.) *Shih nao chih* occurs within talc, in a form like *shih chung huang tzŭ*. It does not, however, occur in every piece of talc. Only one piece of it is obtained by breaking more than one thousand large pieces of talc. Just after the talc is broken, the *shih nao chih* is found in the talc variegated, bright, and fluid. By taking one *shêng* of it, the eater will achieve an age of one thousand years.

97.) *Shih liu huang chih* occurs in all the Five Sacred Mountains, but chiefly in Mt. *Chi* 箕 (in the southeast of *Têng-fêng* District, *Ho-nan* Province). People there say that *Hsü Yu* achieved longevity by taking it here. After that he did not think about wealth and official rank, and refused an offer of the throne from *Yao* 堯 (who reigned B. C. 2357–2255?). That which is called *shih liu tan* 石硫丹 is *ch'ih ching* 赤精 (red essence) of stone and probably belongs to the category of *shih liu huang* 石硫黃. All of them occur on cliffs. The moist one may be taken in the form of pills, the hardened one in the form of powder. There are one hundred and twenty kinds of *shih chih* similar to those mentioned above. They are described in the Books, *T'ai i yü ts'ê* 太乙玉策 and *Ch'ang yü* 昌宇 (or *tzŭ* 字) *nei chi* 內記. They cannot all be mentioned here.

98.) And wood *chih:* The resin from pine and cypress drops on to the ground. After a thousand years it changes into *fu-ling* 茯苓 (*Panchyma cocos* Fries.). A small tree having a shape similar to that of a lotus-flower springs up over the latter after ten thousand years. It is called *mu wei hsi* 木威喜 *chih.* It is bright in the night. One is slippery to the touch. It is not combustible. If carried, it is of use to protect the possessor against weapons. If a hen or a cock which carries *mu wei hsi chih* is put in a cage with twelve other hens or cocks, if then they are shot at with arrows twelve times from a distance of twelve paces, all will be wounded except the fowl which carries *mu wei hsi chih*. It is gathered over *shêng mên* 生門 (the living door), and is dried in the shadow of *Liu chia* 六甲 (a charm). After one hundred days it is pulverized and is then taken three times a day, each time one *fang ts'un pi.* An age of three thousand years will be achieved if one piece of it is finished.

99.) The lower root of a thousand-year old juniper is shaped like a sitting person. Its length is seven *ts'un*. A red sap flows if it is cut into. If the red sap is painted on the bottom of one's foot, one may walk on the surface of water without sinking; if on his nose, then water will open if he goes into it and he may live on the bottom of a river; if on his body, then he will disappear. If he wishes to reappear, then it is wiped off. It can also be used to cure diseases. If the disease is inside the belly, then one *tao kuei* of it is scraped off from the tree and is taken. For outer swelling and pain, one *tao kuei* is scraped off and is rubbed onto the place of swelling and pain. The swelling and pain will be cured at once. If there is a disease on the left foot, it is scraped off and sprinkled on the left foot. If it is scraped off and is mixed with sesame to make a candle which is used at night to illuminate the ground, wherever there is buried treasure of gold and jade the flame will change to a green color and bend downward. Then treasure can be obtained by digging with a spade. If the red sap is pulverized and ten *chin* of it is taken, then an age of one thousand years will be achieved.

100.) Again, there is an accumulated resin under the bark of the branches of a three-thousand-year pine. Its shape is like that of a dragon. It is called *jih fei chieh* 日飛節 *chih.* A large piece weighs ten *chin*. If ten *chin* of the pulverized material is taken, an age of five hundred years will be achieved.

101.) *Fan t'ao* 樊桃 *chih:* Its tree is like a rising dragon. Its flower and leaf are like *tan lo* 丹羅. Its seed is like a hen kingfisher. It is only five *ch'ih* high. It occurs on the north side of famous mountains, and above springs which flow eastward. It is sought for on the day when summer begins (zodiacal position of the sun: Taurus), and is taken after having been pulverized. After one tree is finished, an age of five thousand years will be achieved.

102.) *Ts'an ch'êng* 參成 *chih* is red and bright. Its branches and leaves, when struck, make a sound like that of metal and stone. Being rejoined after breaking, it seems to be the same as before.

103.) *Mu ch'ü* 木渠 *chih* is parasitic on large trees, and like a lotus flower; a cluster has nine stalks. It tastes sweet and acrid.

104.) *Chien mu* 建木 *chih* occurs at *Tu-kuang* 都廣. Its bark is like a *ying-shê* 纓蛇 (a certain snake). Its seed is like a *luan niao* 鸞鳥 (a certain bird).

105.) A person who obtains and takes any of these three *chih* will rise to heaven during the daytime.

106.) The three *chih, huang lu tzŭ* 黃盧子, *hsün mu hua* 尋木華 and *hsüan i hua* 玄液華 occur at *Yao-hsiang* 要鄉 and *Fêng-kao* 奉高 on Mt. *T'ai* 泰 (in Shantung Province). If any of them is obtained and taken, an age of one thousand years will be achieved.

107.) *Huang nieh tan huan* 黃蘗檀桓 *chih* is the lower root of a *Pterocarpus indicus* Willd. of an age of one thousand years. It is like a three-*hu* measure (i. e. like a pyramid with the top half cut off), is one or two *chang* from the upper root, and is connected by fine thread-like roots to the upper root. If it is obtained and is taken after grinding, *ti hsien* 地仙 will be achieved and the eater will be immortal after one piece is finished.

108.) There are also one hundred and twenty species of these, for which there are drawings.

109.) Grass *chih*. Self-moving *chih* moves when the wind is still. Its stalk is as large as a finger and as red as *tan su* 丹素. Its leaves are like *hsien* 莧. The root is a large tuber like a *tou* surrounded on all sides as if by satellites with twelve small tubers as large as hen's eggs. The small tubers are a little more than one *chang* from each other, and are connected with fine roots like white hairs. It occurs in the deep valleys of high mountains. In the places where it occurs, there are no other grasses. The large tuber is obtained, powdered and taken; an age of one thousand years will be achieved if it is finished. An age of one hundred years will be achieved if one small tuber is finished. They may also be given to others to take them. The person who puts the large root in his bosom will disappear (become invisible). If he wishes to reappear, he turns toward the left and takes it out.

110.) Cow (or ox) horn *chih* occurs at Mt. *Hu-shou* 虎壽 and at *Wu Fan* 吳坂. Its shape is like that of a Welsh onion (*Allium fistulosum*, L.), shooting out like the horns of a cow (or ox). It is three or four *chang* high and is blue. It is powdered and is taken three times daily, each time one *fang ts'un pi* 方寸匕. At the end of one hundred days, an age of one thousand years will be achieved.

111.) *Lung* (dragon) *hsien* 龍仙 *chih* looks like a rising dragon (or rising dragons) carrying another rising dragon (or other rising dragons) on its back. If its leaves are considered as the scales of a dragon, then its root is like a coiling dragon. An age of one thousand years will be achieved if one piece of it is taken.

112.) *Ma mu* 麻母 (mother of hemp) *chih* is like hemp, but with a red stalk and with purple flowers.

113.) Pearl *chih* has yellow flowers and red leaves. Its seeds are like plums and of a purple color. Oftentimes twenty-four seeds are connected with each other and hang down like a string of pearls.

114.) *Pai fu* 白符 *chih* is four or five *ch'ih* tall. It is like *Prunus mume* S. & Z. It often blooms during a heavy snow. It bears seeds in the twelfth moon.

115.) *Chu ts'ao* 朱草 *chih* has nine crooks. There are three leaves for each crook, and three seeds near each leaf.

116.) The shape of *wu tê* 五德 *chih* is like that of a tower or a hall. Its stalk is of square cross-section. Its leaves are variegated. The leaves of each hue form a group and do not mingle with one another. The upper part is like a *yen-kai*. In the middle part there is always sweet dew. A purple atmosphere rises from it to a height of about several *ch'ih*.

117.) *Lung hsien* 龍銜 *chih* grows in pairs in the second moon. It has three knots and twelve branches. Its lower root is shaped like a person in a sitting position.

118.) There are one hundred and twenty species of grass *chih*. All are taken after being dried in the shade. The person who takes them will live as long as heaven and earth, or will have an age of one or two thousand years.

119.) Flesh *chih*. *Ch'an ch'u* 蟾蜍 (a striped toad) of an age of ten thousand years has a horn on its head. There are eight red characters on its jowl. Its body is heavy. It is caught at noon of the fifth day of the fifth moon, and is dried one hundred days while shielded from direct sunlight. If the ground is scratched with its left foot, then the earth will change into flowing water. If its left forefoot is carried by a person, it protects him against the five kinds of weapons. If an enemy shoots at him the bow, the crossbow and the arrow will turn their direction and will shoot at the enemy himself.

120.) A bat of an age of one thousand years is as white as snow. It settles with its head downward because of its heavy brains.

121.) If either of these two beings is caught and is taken after being dried in the shade and after being powdered, an age of forty thousand years will be achieved.

122.) The spiritual tortoise of an age of one thousand years is variegated. The male one has two bones on its forehead projecting outward like horns. It is washed with the blood of a goat (or a sheep). Its shell is taken off. After being baked and pounded, its inner part is taken, three times daily, each time one *fang ts'un pi*. An age of one thousand years will be achieved after one such tortoise is eaten up.

123.) If you travel in a mountain, you will see the little person, seven or eight *ts'un* tall, riding in a cart or on horseback. It is a flesh *chih*. If it is caught and is taken (eaten, ingested), you will become a *hsien* at once.

124.) *Fêng shêng shou* 風生獸 is like a sable (*Musana tela zibelina* L.), green and as large as a wild cat. It lives in the great forest of *Nan Hai*. It is caught by setting a net. If it is burned with many cartloads of firewood, although the firewood is burned completely, yet the animal remains incombustible in the ash. Its hair is not charred. Its skin cannot be broken by hacking or pricking. It is like a skin bag when it is beaten. It is killed by striking its head many thousands of times (or tens of times) with a hammer. After being killed, if its mouth is opened toward the wind, it becomes alive again and stands up to walk. By stuffing up its nose with the calamus (*Acornus calamus*) which occurs on stones, it is killed at once. Its brain is taken after being mixed with chrysanthemum. After eating up ten *chin*, an age of five thousand years will be achieved.

125.) The opening of the nest of the swallow of an age of one thousand years faces north. Its color is white and its tail points upward. It is caught and is dried in the shade. After a swallow of such a kind is powdered and is taken, an age of five hundred years will be achieved.

126.) There are one hundred and twenty species of flesh *chih*.

127.) Mushroom *chih* occur in the center of a mountain, or under a large tree, or beside a spring. Their shape is like that of a building, or of a horse and cart, or of a dragon and a tiger, or of a man, or of a flying bird. Their colors vary. There are also one hundred and twenty species. There are drawings of them. They should all be gathered by approaching them with *yü pu*. They are cut with a bone knife. Then they are dried in the shade, powdered and taken. One *fang ts'un pi* of any of them causes the eater to rise up to be a *hsien;* that of a middling mushroom *chih* gives an age of several thousand years; and that of an inferior one an age of one thousand years.

128.) If you enter a famous mountain for the purpose of seeking for *chih*-grass, you must do it in the third and the ninth moon. These are the months when a mountain opens and *shên* medicine appears (can be found). You do not go into a mountain on the day of *Shan-hêng* 山佷. You must go into a mountain at the *ta-fu* 大輔 hour, preferably at *san ch'i hui* 三奇會 (Three Rarenesses Meet Together).[34] You go through the Lucky Door of Three Rarenesses. You arrive at the mountain on the Day *Liu-yin* 六陰, and at the *ming t'ang* 明堂 hour. When entering the mountain, you carry the *Ling pao fu* 靈寶符 (Charm of *Ling pao*), lead a white dog, carry a hen or a cock in your arms, put one tou of white salt onto a large stone, attach the *k'ai shan fu hsi* 開山符檄 (Charm and Message for Opening a Mountain) to a large stone, and hold a handful of *wu t'ang ts'ao* 吳唐草 (or *hua* 花). Then the *shên* of the mountain will be happy and *chih* will surely be obtained. Furthermore, the gathering of *chih* and the eating of *chih* are best practiced on the Day of *Wang hsiang chuan ho* 王相專和, for the two characters of the name of the day in the systems of the stems and branches produce each other.[35]

129.) All these *chih* occur in famous mountains. But common *tao shih* do not devote themselves completely (to learning *hsien*); they are immoral, and do not know the method of entering a mountain. Even if they have drawings of the *chih*, if they do not know their shapes, they still cannot get them. No matter whether a mountain is large or small, every mountain has *kuei* and *shên*. If the *shên* and the *kuei* do not give *chih* to a man, he will not see the *chih* even if he treads on them.

130.) There are five kinds of mica. Most human beings cannot distinguish them. They are distinguished by a careful examination of their colors against the sun. In a dark place the various colors cannot be detected. The variegated one in which green predominates is called cloud flower. It should be eaten in spring. The one in which red predominates is called cloud pearl. It should be eaten in summer. The one in which white predominates is called cloud fluid. It should be eaten in autumn. The one in which black predominates is called cloud mother. It should be eaten in winter. That of only two colors, namely green and yellow, is called cloud sand. It should be eaten in the last moon of summer. That which is transparent and of a pure white color is called *lin shih* 磷石. It may be eaten at all times during the four seasons.

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[34] According to the *Tz'ŭ yüan*, *i* 乙, *ping* 丙 and *ting* 丁 are the Three Rarenesses in the Heaven; *chia* 甲, *wu* 戊 and *kêng* 庚 are the Three Rarenesses under the Earth; and *hsin* 辛, *jên* 壬 and *kuei* 癸 are the Three Rarenesses in the Human World.

[35] *T'ien kan* 天干 or the Heavenly Stems (ten characters) are used in combination with the *ti chih* 地支 or the Branches of Earth (twelve characters) to give names to the sixty days of the Chinese cycle.

131.) The five sorts of mica are eaten by changing them into a solution with *kuei ts'ung shui yü* 桂葱水玉 or by exposing them to the air during the night in an iron vessel, then heating with *hsüan shui* 玄水 (black water), or by burying them after they are enclosed in a cylinder with niter. Or they are mixed thoroughly with honey to form a cream. Or they are dipped in autumn dew one hundred days and then made into a powder in a leather bag. Or they are taken together with *wu tien ts'ao* 無巔草 and the sap of *Ailanthus glandulosa* Desf. If they are taken for one year, all diseases will be cured; if for three years, an old man will be changed into a young boy; if for five years, the eater will be able to control *kuei* and *shên*, will not be burned in a fire, will not be wetted in water, will not be injured by treading on a thorn, and will meet *hsien*. Again, other substances will decay at once if buried, and will be charred at once if burned, but the five sorts of mica are not combustible if they are put in a strong fire for a long time, and they have never decayed if buried. So they are able to confer longevity on human beings. Again it is said, that the clouds are always over the eater if they are taken for ten years. It is natural that the taking of the mother (cloud mother) attracts the son (the cloud).

132.) That which has a gloomy black color when it is looked through against the sun cannot be taken, for it causes *lin* 淋 disease and a boil or an ulcer. Even if it is taken after having been put into solution, it should first be dipped in rain water which has dripped from a thatched hut, or in water flowing eastward, or in dew, in each case for one hundred days; then the earth is discarded and the stone is now useful.

133.) *Wei Shu-ch'ing* 衛叔卿 of *Chung-shan* 中山 was able to ride on the clouds after he took mica for a long time. He enclosed his recipe in a jade box. After he became *hsien*, his son, *Ming-shih* 名世 and *Liang Po* 梁伯, a *shih-chê* 使者 (title of an officer) of the *Han* dynasty, obtained the recipe. They prepared it and ate it according to the recipe. All became *hsien*.

134.) Again, realgar which occurs at Mt. *Wu-tu* 武都 is pure. Only that which is as red as a cock's comb, lustrous and transparent may be used. That which is pure yellow, like the (ordinary) color of realgar, but without red luster, cannot be used to prepare *hsien* medicine. It may be used only for preparing medicines for curing diseases. Methods of taking realgar: sometimes it is cooked; sometimes it is taken with wine, or after being changed into a solution with niter, it is congealed; or it is enclosed in *hsüan t'ung ch'ang* 玄胴腸 and is cooked under *chih t'u* 赤土 (red earth); or it is mixed with resin from pine; or it is heated with *san wu* 三物 and then it is drawn out like cloth which is as white as ice. If it is taken in any of these forms, it confers longevity, frees the eater from diseases, rids him of the three *shih* 尸,[36] rids him of scars and marks on the skin, changes white hair into black, and causes teeth to grow again. If it is taken for one thousand days, the jade maid comes to attend the eater. She can be used to summon *hsing ch'u* 行厨. Moreover, the true jade maid is attested by the yellow jade, which is as large as a millet seed, on her nose. Lacking this testimony, it is only a devil testing a human being (to see whether he is moral).

135.) Jade is also *hsien* medicine, but it is difficult to procure. *Yü ching* 玉經 (The Book of Jade) says: "The age of those who take gold is as old as that of gold; jade, as old as that of jade." And, "The life of those who take *hsüan-chên* 玄眞 (Mysterious Truth) is without end." *Hsüan-chên* is the alias of jade. It causes the eater to fly up to be a *hsien* in heaven, not merely to be a *ti hsien* (immortal of the earth). But its effect is slow. After one or two hundred *chin* have been taken, then its effect can be detected. Jade can be changed into a solution[37] by the liquor from *Wu mi* 烏米 (black rice) and the liquor from *Poterium officinale* Bth. & H. f. It may be dispersed by a paste of Welsh onion (*Allium fistu-*

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[36] The three spirits of the human body. The first lives in the brain, the second in the *ming t'ang*, and the third in the belly and stomach. They are able to cause trouble to a man.

[37] Literally *water*, as elsewhere in this chapter; possibly a liquid which is not a true solution.

losum L.) to form a sugarplum. It can be made into a pill. It can also be burned to form a powder. After it has been taken for more than one year, the eater will not be wetted if he goes into water, will not be burned in a fire, will not be wounded by a sword and will not be attacked by poisonous creatures. But jade utensils may not be used. They cause troubles to human health, and are of no benefit. Uncut jade should be obtained and then this may be used. White jade from the state of *Yü tien* 于闐 (*Khotan*) is best; next, that from *Hsü Shan T'ing Pu Chieh* 徐善亭部界 in *Nan-yang*, or jade of the river *Lu-jung* 盧容 in *Jih-nan* 日南. *Ch'ih Sung Tzŭ* took the solution made by dipping jade in the blood of *hsüan-ch'ung* 玄蟲 (black insect). In consequence he was able to ascend and descend by riding on smoke. Jade powder, if taken alone or with water confers immortality. Jade is not as good as gold. Its eater will often be feverish, as happens after taking *han shih san* 寒食散.[38] Those who take jade powder should take realgar and cinnabar once every ten days, each time one *tao kuei*. Then they should dishevel their hair and bathe in cold water, and take a walk against the wind. Then they will not be feverish. *Tung Chün-i* 董君異 once gave the liquor of jade to a blind man to drink. After ten days the blind man's eyes were cured. Wishing to take jade, *Wu Yen-chih* 吳延稚 obtained a recipe from the *Yü ching*, but did not understand it thoroughly. He did not know its limits and taboos. He collected various jade ornaments with the intention of taking them. Afterwards I told him that these were useless. He sighed: "The matter should not be partially understood. The taking of these jades is not only not beneficial, but also I have almost suffered a calamity."

136.) Again, silver. It is not, however, as good as gold and jade. It may make a man a *ti hsien* (earthly immortal). It may be taken either after being changed with the paste of wheat (or barley or oats) or with the liquor from *chu-ts'ao* 朱草, or after being fused with *lung-kao* 龍膏. But three doses of it should be taken, each as large as a bullet. So much silver can not be gotten by poor *tao shih*.

137.) A pearl of a diameter of over one *ts'un* confers longevity after it is eaten. It is dispersed to form something like quicksilver by dipping in the milk of a domestic animal. It may be drawn to the length of three or four *ch'ih* if prepared with float-stone (pumice) or bees' nest (wax) or iron pyrites. Then it is eaten after being made into pills. The eater will be immortal if he takes it while he abstains from grains.

138.) If clear and non-sticky lacquer (from *Rhus vernicifera* or *Vernix vernicia*) is taken, the eater will be on good terms with *shên* and will live long. It is taken by putting ten large crabs into it, or together with the solution of mica or the solution of jade. Then the nine parasites will all be driven out. Bad blood will be driven out through the nose. After it has been taken one year, *liu chia* and *hsing ch'u* 六甲行廚[39] will arrive.

139.) Cinnamon may be changed into a solution by heating on a water bath with the juice of a Welsh onion. It may be taken with bamboo sap. It may also be taken after being mixed with *hsien chih chün nao* 先知君腦 or tortoise. After it has been taken seven years, the eater can walk on water and will be immortal.

140.) The eater of sesame will not become old, and will withstand wind and moisture. It nourishes against being worn out with old age.

141.) The mucilage from the peach tree may be taken by dipping it in the water extract from the ashes of a mulberry tree. In this way it cures diseases. After it has been taken for a long time, the body of the eater will be light and bright. In a dark night he will be as bright as the rising of the moon. If much of the mucilage from the peach tree is taken, the eater may abstain from grains.

142.) If the red (one of the *chih* of the) seed of *Broussonetia papyrifera* Vent. is taken for a year, an old man will change into a younger one. It causes the eater to be able to see a *kuei* (ghost). Formerly, a *tao shih*, *Liang Hsü* 梁須, became younger after he had taken it at the age of seventy years. When he was one hundred and forty years old, he could write in the dark and could run as fast as a galloping horse. Later on he went into Mt. *Ch'ing-lung* 青龍.

143.) The seeds of *Sophora japonica* L. are sealed up with earth in a new jar for twenty odd days. The outer skin becomes completely soft. It is washed away. The material now looks like soya bean. It is taken daily. It nourishes the brain. After it has been taken for a long time, the hair of the eater will not become white and the eater will live long.

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[38] There is a long article (in Chinese) on this medicine: *Yü Chia-hsi*, 余嘉錫 *Han-shih-san k'ao* 考 in *Fu-jên hsüeh-chih* 輔仁學誌 **7.** 29–63. (1938).

[39] Or *liu-chia hsing-ch'u?*

144.) *Hsüan-chung-wan* 玄中蔓, *fang-ch'u* 方楚, *fei-lien* 飛廉, *Alisma plantago* L., *Rehmannia glutinosa* Lib., *Coptis teeta* Wall., etc., in total three hundred odd species, are all able to prolong human life. Each may be taken alone.

145.) *Ling fei san* 靈飛散, *wei yang wan* 未央丸, *chih ming wan* 制命丸 and *yang hsüeh wan* 羊血丸 all confer longevity on the eater.

146.) In the mountain in the district of *Li* 酈, in *Nan Yang*, there is the Sweet Valley Stream. Its water is sweet because sweet chrysanthemum grows by the stream, the flowers drip into it, and after many generations the taste of the water has changed. All the people who live in the valley sink no well, but drink the water from it. All the people who drink the water die of old age. Some die at an older age, like one hundred and forty or fifty years; some at a younger age, like eighty or ninety. None dies young. This is due to the effect of the chrysanthemum. Therefore *ssŭ-k'ung* 司空 *Wang Ch'ang* 王暢, *t'ai wei* 太尉 *Liu K'uan* 劉寬 and *t'ai fu* 太傅[40] *Yüan Wei* 袁隗, who each at one time had been *t'ai shou* of *Nan Yang*, when they came into office, always ordered the District of *Li* to send the water from the Sweet Valley Stream to them for drinking, forty *hu* monthly. Most of them had formerly been sick of *fêng-pi* 風痺 and *hsüan-mao* 眩冒, and they all were cured. But they did not have as great benefit as the people who lived in the Sweet Valley and used the water all their lives. Again, the flowers of chrysanthemum and *i* 薏 are similar. They are only distinguished by their sweetness and bitterness. Chrysanthemum is sweet, while *i* is bitter. Therefore the proverb says: "as bitter as *i*." Now there is true chrysanthemum everywhere, but not very much. It often occurs beside water, most abundantly at Mt. *K'ou Shih* 緱氏 and in the District of *Li*. *Jih-ching* 日精, *kêng-shêng* 更生 and *chou-ying* 周盈 in *hsien* recipes are all names of chrysanthemum, and the names of its root, stalk, flower and seed are different. The descriptions praise chrysanthemum very much. But now there is scarcely any effect if it is taken. This is due merely to the fact that no true chrysanthemum is obtained. That the water of the Sweet Valley Stream retains the odor and taste of the chrysanthemum is not worthy of special mention. However, the people who live in the valley have their lives prolonged by it. Then is a good medicine not beneficial?

147.) My late grandfather *hung-lu* 鴻臚 (title of a high officer) *Shao-ch'ing* 少卿, who had been a magistrate of *Lin-yüan* 臨沅 said: "In this district there was the *Liao* 廖 family whose members have been long-lived for generations (died of old age). Some died at the age of one hundred, some at eighty or ninety. Afterwards they changed their residence and since then the members of the family for the most part have died young. Other persons who lived in the house of the family also died of old age generation after generation. They then understood that the effect was due to the house, but they did not know why. Suspecting that the water of the well in the house was very red, they tried excavating the place beside the well. Tens of *hu* of cinnabar buried by the ancients were obtained at a place several *ch'ih* distant from the well. The sap (solution, suspension, extract) of the cinnabar flowed gradually into the well by the way of a spring. Therefore the water of the well was able to confer old age if it was drunk." There will be a much greater effect if cinnabar is eaten after it has been treated.

148.) Again, I have heard that in *Shang-tang* 上黨 there was a man *Chao Ch'ü* 趙瞿 who was sick of leprosy for many years. He was treated, but there was no effect and he was at death's door. Someone said: "It is rather better that he should be abandoned (isolated) while he still lives!" Later on, his posterity were infected from one to another. Then his family put him in a cave on a mountain, with food. Grieving over his misfortune by day and by night, he cried for nearly a month. Then a *hsien* passed before the cave. Seeing him, the *hsien* took pity on him. The *hsien* asked him why he was so. He knew that the man was an extraordinary person. Knocking his head on the ground, he told the *hsien* of his misfortune and implored aid. Then the *hsien* gave him a bag of medicine, and told him how to take it. He took it one hundred and odd days. All the ulcers were cured. He had a plump countenance and good skin. The *hsien* came to see him again. He thanked the *hsien* for saving his life and begged for the recipe for the medicine. The *hsien* told him: "It is the resin from pine. There is much of it even in this mountain. If you prepare it and take it, longevity will be achieved." Then he returned home. His family considered him a *kuei* at first, and was very much astonished. He continued always to take the resin from pine. His body turned lighter. His strength increased very much. He did not become tired if he climbed steep places and passed over dangerous places all day long. When he was one hundred and seventy years old, his teeth were not gone and his hair had not turned white. Sleeping at night, he suddenly perceived that in his room there was a light as large as from a mirror. He asked others beside him, but they all said that they did not see it. The light became larger and larger; the whole room became as bright as in the daytime. At night he saw that on his face there were two girls with colored clothes, two or three *ts'un* tall. They both had faces and bodies (they were like real people), but they were small. They played between his mouth and nose for one year. Then these girls grew up gradually, and were present beside him. Hearing the sound of *ch'in* 琴 and *sê* 瑟, he always laughed alone pleasantly. He lived in the human world three hundred and odd years with a countenance like that of a young boy. Afterwards he went into Mt. *Pao-tu* 抱犢. He must be a *ti hsien*. Having heard the story, people vied with one another in eating the resin from pine. The rich conveyed it by cart or by donkey, and piled it up so as to fill a room. But on perceiving no great effect after eating it at most for one month only, they stopped. So difficult is it to find people with resolution.

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[40] *Ssŭ k'ung, t'ai wei* and *t'ai fu* are the titles of high officers.

149.) Again during the reign (32–5 B. C.) of *Han Ch'êng ti* 漢成帝, a huntsman saw a person without clothes, with black hair on the body, in Mt. *Chung Nan* 終南. He tried to pursue and seize the person, but the latter jumped over pits and valleys as quick as flying, and could not be seized. Then the person was spied upon secretly and was captured after being surrounded. It was then that the person was ascertained to be a woman. She was questioned, and said: "I am a lady of the palace of the *Ch'in* 秦 dynasty. Hearing that the rebels from the east of the *Han-Ku* 函谷 Pass had arrived, the king of the *Ch'in* 秦 dynasty yielded, and the palace was burned. Astonished, I escaped into the mountain. Having nothing to eat, I was on the eve of dying of hunger. An old man taught me to eat the leaves and seeds of pine. At first I felt that they tasted very astringent. Afterwards I became accustomed to them. Since that time I have not been hungry and thirsty, and have not felt cold in winter and hot in summer." This woman must have been a lady of the palace of king *Tzŭ-ying*[41] 子嬰 of the *Ch'in* dynasty. Up to the reign of *Han Ch'êng-ti*, she had attained an age of three hundred and odd years. She was brought back and cereals were given her to eat. At first she vomited for many days on smelling the odor of cereals. Afterwards she became accustomed to them. After a little more than two years, the hair on her body was gone. Later on she became old and died. If she had not been seized, she would have become a *hsien!*

150.) The *Wên* 文 family of *Nan-yang* relate that their ancestor escaped into a mountain during the great disorder at the end of the *Han* dynasty. He was hungry, tired and almost dead. A person taught him to eat *shu*. Then he was not hungry. After tens of years, he returned home younger and stronger than before. He told how his body had been so light in the mountain that he could jump with ease. He had not been fatigued by climbing up to high places or by passing over dangerous places for many days. He had not felt cold while walking on snow and ice. He had seen that there were many persons, sitting opposite on a high stone, who were playing chess (or a similar game). One of these, who had read books, looking downward and seeing him, had scrutinized his countenance, and had asked the others: "May this person be called to come up (i. e. to participate in the playing of chess)?" One had answered: "Not yet."

151.) *Shu* is also called *shan-chi* 山薊 (mountain thistle) and *shan-ching* 山精 (mountain essence). Therefore the *Shên-yao-ching* 神藥經 (Book of Divine Medicines) says: "If you must desire (insist on getting) longevity, take always *shan-ching*." Formerly each of the *hsien*, the Eight *Kung* 公 (who had come to the court of *Huai-nan wang* 淮南王) took one medicine to achieve *lu hsien* 陸仙 (continent immortal). After many hundred years, each prepared *shên tan* 神丹 (divine medicine) and *chin i* (gold fluid), and then rose up to *t'ai ch'ing* 太清. If one treats the Eight Substances[42] together and takes them their benefits will not be obtained, for their effects cancel each other.

152.) *Han Chung* 韓終 took calamus (*Acornus calamus*) thirteen years. His body was covered with hair. He read ten thousand characters daily. Afterwards he could repeat all of them from memory. He did not feel cold when he put no clothes on in winter. The calamus which grows on a stone, with five knots in one *ts'un* and with purple flowers, is especially good to be gathered.

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[41] The nephew and successor of Êrh-shih huang-ti.

[42] Namely, cinnabar, realgar, *k'ung ch'ing* 空青, sulfur, mica, soda-crystal, nitre and orpiment.

153.) *Chao T'a-tzŭ* 趙他子 took cinnamon twenty years. Hair grew on the soles of his feet. He could walk five hundred *li* daily, and could lift a weight of one thousand *chin.*

154.) *I-mên-tzŭ* 移門子 took seeds of *Schizandra chinensis* Baill. sixteen years. His coutenance was like that of a jade maid. He went into water without being wetted, and into fire without being burned.

155.) *Ch'u Wên-tzŭ* 楚文子 took *Rehmannia glutinosa* Lib. eight years. He was able to see things at night, was bright (luminous) and was very strong.

156.) After taking *shu* eleven years, the ears of *Lin Tzŭ-ming* 林子明 were five *ts'un* long. His body was so light that he could fly. He could jump over a deep valley of two *chang* and more in width.

157.) *Tu Tzŭ-wei* 杜子微 took *Asparagus lucidus* Ldl. He had eighty concubines and one hundred and thirty sons. He could walk three hundred *li* daily.

158.) *Jên Tzŭ-chi* 任子季 took *Panchyma cocos* Fries. eighteen years. *Hsien* and jade maidens came to follow him (to associate with him). He could disappear and reappear. He did not eat cereals. The scars from singeing all disappeared. His face and body had the luster of jade.

159.) *Ling-yang Tzŭ-chung* 陵陽子仲 took *Polygola sibirica* L. (and *Polygola tenuifolia* Willd.) twenty years. He had thirty seven sons. Books which he once looked over were never forgotten.

160.) The *Hsien ching* says: "Although an age of many hundred years has already been attained by eating the leaves of a grass or of a tree, do not neglect the *shên tan* or else *hsien* will still not be achieved." From these words (it appears that) grass and trees can only prolong life. They are not the medicines for immortality. They may however be taken for supporting the eater if he has not yet been able to prepare the *tan.*

161.) Someone asks: Should some medicines be taken before eating, and others after eating? *Pao-p'u-tzŭ* answers: According to *Chung-huang-tzŭ fu shih chich tu* 中黃子服食節度 (*Chung-huang tzŭ*'s regulations on eating), 'The medicine for curing diseases is taken before eating, for nourishing human nature after eating.' I asked *Chêng chün* why it was so. He said: 'It is easy to understand. If a medicine is used for curing a disease, then it should be taken before eating when the internal organs are empty and cold, and the effect of the medicine will be easily secured. If it is taken after eating, the medicine merely attacks the cereals, and the strength of the medicine is then exhausted. For nourishing human nature, if a medicine is taken before eating, then its effect is not secured, but it is carried down by the cereals. The carrying down cannot be hindered. There will be no benefit.'

162.) *Pao-p'u-tzŭ* answers: According to *Yü-ts'ê-chi* 玉策記 and *K'ai-ming-ching* 開明經, the fates of persons are all known from the five musical notes[43] and six categories: *tzŭ* and *wu* 午 belong to *kêng, mao* 卯 and *yu* 酉 belong to *chi* 己, *yin* 寅 and *shên* 申 belong to *wu* 戊, *ch'ou* 丑 and *wei* 未 belong to *hsin, ch'ên* and *hsü* 戌 belong to *ping,* and *ssŭ* 巳 and *hai* 亥 belong to *ting.*[44] First note: those getting it are *kung* 宮 and earth. Third note: those getting it are *chi* 徵 and fire. Fifth note: Those getting it are *yü* 羽 and water. Seventh note: those getting it are *shang* 商 and metal, and ninth note: those getting are *chio* 角 and wood. If the fate of a person belongs to earth, it is not suitable for him to take green medicine; if to metal, red medicine; if to wood, white medicine; if to water, yellow medicine; and if to fire, black medicine; for according to the principle of the five elements, wood destroys earth, earth destroys water, water destroys fire, fire destroys metal, and metal destroys wood. As for the great medicines of *chin* and *tan,* the question of suitability or unsuitability does not come into consideration."

163.) First, *kung:*

kêng-tzŭ, kêng-wu;	庚字庚午
hsin-wei, hsin-ch'ou;	辛未辛丑
ping-ch'en, ping-hsü;	丙辰丙戌
ting-hai, ting-ssŭ;	丁亥丁巳
wu-yin, wu-shên;	戊寅戊申
chi-mao, chi-yu.	己卯己酉

Third, *chi:*

chia-ch'ên, chia-hsü;	甲辰甲戌
i-hai, i-ssŭ;	乙亥乙巳
ping-yin, ping-shên;	丙寅丙申
ting-yu, ting-mao;	丁酉丁卯
wu-wu, wu-tzŭ;	戊午戊子
chi-wei, chi-ch'ou.	己未己丑

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[43] The five musical notes: *kung* 宮, *shang, chio, chi* and *yü.*

[44] These form twelve of the sixty cyclical binoms.

Fifth, *yü:*

chia-yin, chia-shên;	甲寅甲申
i-mao, i-yu;	乙卯乙酉
ping-tzŭ, ping-wu;	内字内午
ting-wei, ting-ch'ou;	丁未丁丑
jên-ch'ên, jên-hsü;	壬辰壬戌
kuei-ssŭ, kuei-hai.	癸巳癸亥

Seventh, *shang:*

chia-tzŭ, chia-wu;	甲子甲午
i-ch'ou, i-wei;	乙丑乙未
kêng-ch'ên, kêng-hsü;	庚辰庚戌
hsin-ssŭ, hsin-hai;	辛巳辛亥
jên-shên, jên-yin;	壬申壬寅
kuei-mao, kuei-yu.	癸卯癸酉

Ninth, *chio:*

wu-ch'ên, wu-hsü;	戊辰戊戌
chi-ssŭ, chi-hai;	己巳己亥
kêng-yin, kêng-shên;	庚寅庚申
hsin-mao, hsin-yu;	辛卯辛酉
jên-wu, jên-tzŭ;	壬午壬子
kuei-ch'ou, kuei-wei.	癸丑癸未[45]

164.) The method of *yü pu* (or The Gait of *Yü*).[46]

1. Lift left foot.
2. Move right foot past left foot.
3. Bring left foot up to right foot.
4. Then lift right foot.
5. Move left foot past right foot.
6. Bring right foot up to left foot.
7. Then lift left foot.
8. Move right foot past left foot.
9. Bring left foot close to right foot.

These three steps should amount to two *chang* and one *ch'ih* (21 feet). There will be nine foot-prints.

165.) The small divine (cinnabar) recipe: Three *chin* 斤 of true cinnabar and one *chin* of white honey are mixed thoroughly. The mixture is exposed to sunlight, and then it is concentrated by heating so that it may be made into pills. Ten pills, as large as sesame seeds, are taken each morning. In less than one year, white hair changes to black, teeth grow again and the body of the eater becomes smooth (like a baby's skin). If the medicine is taken for a long time, an old person changes into a young boy. If it is taken continuously, immortality will be achieved.

166.) A minor recipe for preparing gold for eating: Gold is fused in the fire, and is dipped into clear wine (wine for sacrifice). After two hundred repeated dippings into the wine, and re-fusions and re-dippings, the wine boils. Then the gold is grasped in such fashion that it is pressed out between the fingers by squeezing, then the gold is re-fused and is dipped into the wine again. There is no definite number of the repetitions of the process. After it is accomplished, one pill as large as a bullet is taken. The gold can also be made into a solution (colloidal solution or suspension?). Besides the large pill, the remaining gold is made into small pills. After they are taken for thirty days, the eater does not feel either cold or warm. *Shên* and jade maidens come down (from heaven) to associate with him. Again, silver may also be taken by the same method as gold. After taking these two substances, the eater may live in a stone chamber of a famous mountain for one year, then he will become a *hsien*. In the human world those who take them are called *ti hsien*. Do not tell this recipe to others recklessly.

167.) Recipe for *Liang-i tzŭ*'s 兩儀子 preparation of gold for eating: Fat from the lower side of the neck of a pig, three *chin;* clear vinegar, one *tou*. Five *liang* of gold is heated in a utensil. Then the gold is taken out of the furnace and is put into the fat. It is put in and is taken out for reheating as many as one hundred times. The vinegar may also be used instead of the fat. If one *chin* of the finished substance is taken, a life as long as heaven and earth will be achieved; if half a *chin*, two thousand years; and if five *liang*, one thousand and two hundred years. Any amount of it may be taken. It should be prepared on the Day of *Wang Hsiang*. This method should not be taught to others, or else the preparation will not be successful.

168.) If the medicine for driving out the three *shih* is desired, cinnabar should be taken. The method of taking cinnabar: One *chin* of cinnabar is pounded and is mixed with three *shêng* of clear vinegar and two *shêng* of clear lacquer (from *Rhus vernifera* or *Vernix vernicia*) (in one edition, two *shêng* of honey) so that the three substances adhere to each other. It is taken two times daily, each time three pills as large as sesame seeds. After it has been taken for forty days, all the diseases in the belly will be cured and the three *shih* will be driven out. After one hundred days, the eater will be strong. After it has been taken for one thousand days, *Ssŭ-ming* 司命 (a *shên*) will remove the eater's name from the book of death. He will live as long as the heaven and the earth, as the sun and the moon. He will be able to change his form and his countenance indefinitely. He will cast no shadow in the sunlight, and will be bright (luminous).

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[45] In this table the five musical notes (and hence the five elements, the five colors of the medicines, etc.) are related to the Ten Heavenly Stems, namely *chia*, *i*, *ping*, *ting*, *wu* 戊, *chi* 己, *kêng*, *hsin*, *jên* and *kuei*, and the Twelve Branches of Earth, namely *tzŭ*, *ch'ou*, *yin* 寅, *mao*, *ch'ên*, *ssŭ*, *wu* 午, *wei*, *shên*, *yu*, *hsü* and *hai*, the names of which were at first used to designate the sixty days and the sixty years of the time cycles. Magical meanings were given later to the single characters and to combinations of them.

[46] Taoists attribute the gait to the Great *Yü*, the founder of the *Hsia* 夏 dynasty (2205–1818 B. C.) from whom it is supposed to have been handed down.

Inner Chapter XII. CLEARING UP CERTAIN QUESTIONS.

169.) Some one asks: If it is sure that *hsien* is possible of attainment, then the *shêng* ought to have devoted themselves to it, but *Chou kung* and Confucius did not do it. It is clear that there has been no *tao* of *hsien*.

170.) *Pao-p'u-tzŭ* answers: A *shêng* is not necessarily a *hsien* at the same time, and a *hsien* is not necessarily a *shêng* at the same time . . . According to the *Hsien ching*, those who achieve *hsien* are all endowed naturally by destiny with the disposition for *shên hsien*. Therefore while they are in the womb (before birth), they already have the disposition to believe in *tao*, and when they have knowledge, they like the *tao* of *hsien*. They must meet enlightened teachers and must acquire their method. Otherwise, they (who are not endowed with the disposition for *shên hsien*) do not believe and do not seek for the tao of *hsien*. Even if they seek it, they will still not achieve it.

171.) A *hsien* is a sage who obtains *tao*, while a sage in general is one who rules over the world. A *hsien* is born to be a *hsien*, and a sage is born to be a sage. A person born to be a *hsien* will become a *hsien* through his effort. *Pao-p'u-tzŭ* describes the differences and similarities between a *hsien* and a common person. Many sages are able to know the *tao* of *hsien*, and people believe that a sage can do and can know everything. Many things which Confucius did not know are described, and so many sages do not know *hsien*. Moreover, there are many mysterious things which certain people can do and sages cannot. Someone says that sages know the way to *hsien* but that they do not care for it, that it is a matter of like and dislike between *hsien* and sages, and that the latter cannot be compelled to devote themselves to *hsien*.

Inner Chapter XIII. SUPREME STATEMENT

172.) Someone asks: In ancient times did people achieve *hsien* by learning or only because of their destiny? *Pao-p'u-tzŭ* answers: Oh! No! They all sought out teachers through the hardships of travel. Then they served their teachers by cleaning the house, and by working, and by ploughing the land. At the first they were examined as to their faith, and at the last they were tested in danger and distress. If their dispositions were honest and their conduct true, and if they had no repining and doubt, then their teachers would teach them their secrets. Some intermitted because of idleness and weariness. Some withdrew because of repining and resentment. Some were attracted by glory and wealth, and returned to engage in the affairs of the common people. Some were betrayed by corrupt speech and lost their resolution to (seek) retirement. Some began in the morning and hoped for success in the evening. Some expected the effect immediately after practicing. It was indeed many if among ten thousand persons there was one who was not attracted away by the sight of wealth and beauty, who was not discouraged when he heard the talk of the common people. In consequence those who studied it were as numerous as the hairs of a cow, but those who achieved it were as rare as the horn of a unicorn . . .

173.) Therefore longevity is not difficult, but to learn the *tao* (to know the method of achieving longevity) is difficult. To learn the *tao* is not difficult, but to put it into practice is difficult. To put it into practice is not difficult, but to bring it to an end (to its object), is difficult . . .

174.) Someone asks: Why is it that some of those who take medicine, practice *hsing ch'i*, or practice *tao yin* in the world do not escape death? *Pao-p'u-tzŭ* answers: Those who do not get *chin* or *tan*, but take medicine made from grass and from trees, and practice lesser arts, may only prolong their lives and delay their death, but they will not achieve *hsien*.

175.) Many *hsien* are described. To become a *hsien*, one must keep himself strong enough and must know how to protect himself against mountain spirits, etc. Among the ways to keep strong are: not to run rapidly, to put on clothes before one feels cold, to eat before one becomes very hungry and not to eat too much, to drink water before one is very thirsty and not to drink too much, and not to expose oneself to intense cold, intense heat, violent wind, or thick mist.

Inner Chapter XIV. EAGERLY SEEKING GOOD TEACHERS.

176.) In the world there are many wicked persons who falsely assume the title of *tao-shih*. They are all however unwilling to admit that they know nothing. They all have some smattering, or they buy their reputation falsely. In addition, they are able to restrain demons and are hypocritical. Officious people who do not know the true and the false come to them to study and suffer from being led astray by their own error. Furthermore, they are detained so that they do not go away (from the false *tao-shih*) to seek for extraordinary people (true *tao-shih*), and the false ones tell them, "Here is all of the *tao*," with the result that many persons of resolution are led astray. It is regretful and hateful. . .

177.) Some who might truly learn the *tao* are not able to seek diligently for a famous teacher to prepare extraordinary medicine, but recite and expound thousands of volumes of books of no importance. They get no effect from them, even if they continue until they become old. Then they say that there is surely no method of *hsien* in the world. . . Students of the future should search for a teacher, but should also select him carefully.

178.) *Tao-shih* teach only seekers who are eager. Human life is short, and one ought to look for a good teacher eagerly and then to study diligently. *Chuang-tzŭ*'s philosophy of equalizing life and death is discredited. One should respect his teacher and should be patient, otherwise his teacher will not tell him all of his secrets. The study of voluminous and useless books and the worship of gods are not effective for achieving immortality. A man may appear to know all about *hsien*, and may have many students, but may really be cheating them by accepting their fees. One's teacher therefore must be selected with care. *Tao-shih* of little learning are jealous of those who really know the *hsien* medicines, and ought to respect them and learn from them. The books of *tao* are voluminous, but none of them is written in as much detail and as concretely as *Pao-p'u-tzŭ*.

Inner Chapter XV. MISCELLANEOUS EFFECTIVE METHODS.

179.) Someone asks: Will abstinence from grains confer longevity? How many methods are there for it? Which is the best one? *Pao-p'u-tzŭ* answers: Abstaining from grains merely economizes the cost of cereals and other foods. This practice alone will not confer longevity. I have asked many persons who have abstained from grains for a long time, and they have said that they have had somewhat less disease and pain than when they have eaten grains. Those who twice daily take *shu*, *huang ching*, and pills of *yü yü liang* 禹餘糧 become stronger and are capable of carrying a burden. On a long journey their bodies are extremely light. Those who take one dose of stone medicine and keep it for ten or for five years, or inhale air, or use charms, or drink *shên* water, lack hunger merely; their strength does not support toil.

180.) Various means, largely magical, are described of tolerating heat and cold, of not being injured by military weapons, of disappearing at will, of changing into the form of an animal, a bird, a stone, a tree, grass, etc., and of escaping from instruments of punishment, also methods of summoning spirits to prophesy luck and of prophesying luck by means of mirrors. Those who know the art of *hsien* will not be sick, but beginners in the art usually study medicine in order to take care of their diseases. Methods of improving the hearing by putting certain materials into the outer ear and of improving the eyes and the teeth by washing with certain medicines are described, and methods of preventing fatigue when travelling over mountains and rivers, of running very rapidly (12000 *li* or about 4000 miles in 24 hours), and of avoiding the attack of epidemics.

Inner Chapter XVI. ON THE YELLOW AND THE WHITE.

181.) A complete translation of this chapter by *Wu Lu-ch'iang* with an Abstract Table of Contents has been published in *Proc. Amer. Acad. Arts and Sciences*, **70,** 256–268, 274–276 (1935).

Inner Chapter XVII. CLIMBING MOUNTAINS AND CROSSING RIVERS

182.) Alchemists prepare medicines in mountains, and so should know how to climb a mountain and how to pass across a river. There is a spirit for each mountain, and a lucky month or day must be chosen for the ascent. Old animals have the ability to change into the form of men, and mirrors are used to detect them. Various magical and medical means are described of protecting oneself against mountain spirits, wild animals, snakes, dragons, cold and moist mountain weather, etc. Realgar is recommended as a cure for snake bite. *Fu* (charms, magical drawings) for the ascent of mountains and for protection against wild animals are pictured and described.

Inner Chapter XVIII. CERTAIN TRUTHS UPON THE EARTH.

183. The metaphysics of One is described and its importance for alchemy is pointed out. The practice of miscellaneous magical methods ought to be given up, but means are described whereby one person may become many persons of the same form and appearance. The student of alchemy ought to work hard at seeking medicines in mountains and rivers and at preparing the medicine, but he will need funds for the purpose. At first he may be a merchant or a farmer in order that he may get enough money to procure the raw materials.

Inner Chapter XIX. EXTENSIVE READING.

184.) *Pao-p'u-tzŭ* gives an account of his teacher, *Chêng chün*, from whom, he says he obtained many secret books. Many books of *tao* are listed. There are many *fu* which are not very effective because errors have been introduced into them by copying. A few most useful books and the mysterious effects (not for *hsien* medicines) which result from their use are described.

185.) Fortunately I met a good teacher, *Chêng chün*. But it is remorseful that I was not wise enough to be able to learn the most advanced principles. It is most remorseful that I did not learn very much, for at that time, although I was serving him as a disciple, I had little acumen, and being still young I did not concentrate my mind on the study—and human desires had not yet all been discarded.

186.) At that time *Chêng chün* was over eighty years of age. He already had some white hair which however became black again after many years. His countenance was plump and cheerful. He was able to draw a strong crossbow and to shoot to a distance of a hundred *pu*. He was able to walk many hundred *li* daily. He was not intoxicated if he drank two *tou* of wine. He climbed up a mountain so rapidly that most young people could not follow him. His food and drink were no different from the food and drink of the common people, and I did not see that he abstained from grains. I inquired of his earlier disciple, *Huang Chang* 黃章 who said: "When he was returning from *Yü-chang* 豫章 (a *chün*, now North *Kiangsi*), *Chêng chün* encountered a strong wind for many days at *Chüeh-kou-p'u* 木屈溝浦. It was said that there were many robbers on the homeward route, and his companions detained him. All of his companions of the journey considered that the food was insufficient, but he gave to others the food which he should have eaten, while he himself ate nothing for fifty days. He was not hungry and I did not see that he did anything (as a substitute for food or as a means of abstaining from grains). I do not know by what means he was able to do this." He could write small characters under a lamp better than a young man. He understood music and was proficient in playing the *ch'in* 琴. While sitting at leisure with many persons sitting in attendance upon him, he answered questions continuously and at the same time corrected the tones of the instrument which someone beside him was playing.

187.) I was a late disciple of *Chêng chün*. I asked to see books of recipes. He told me: "The essential is only one *ch'ih* of silk, which is enough for delivering from the human world. Not many books are necessary. But wide reading is much better than seeing none at all. Elementary methods may be acquired for protecting against the distresses of a beginner." He gradually showed me almost 100 chapters of books of *Taoist* teachings and rules which are not important. I had already seen many of them previously and I asked him about points which I did not understand therein. *Chêng-chün* said: "You have the ability to discern things. You are teachable. Although you have learned much, yet what you have learned is not essential, and, being attentive to outer studies, you cannot concentrate your mind; so you are not yet ready to study the advanced principles. Now I must show you good books." He allowed me gradually to have short books written on white silk. Those which I saw during many years would amount altogether to more than two hundred and odd *chüan* 卷 (rolls of silk or paper), but I could not obtain them. Other disciples served him by gathering fuel and by plowing. I alone, being feeble, could serve him only by dusting and by wiping the couches and tables, by grinding ink on a palette, by holding his light, and by copying ancient books for him. He treated me the same as the earlier disciples. He told me: "There are good things in every *chüan* of miscellaneous *tao shu* 道書. They should be discerned, and the good things should be selected out from them, and these should be practiced. It is not necessary to waste time and energy by memorizing all of them. If the *chin tan* is once prepared successfully, all these will be discarded. When there is something to be taught, the essentials (trunk and twigs) should be gotten. To inspire progress, begin with the elementary. The student never wishes to go step by step.

188.) *Chêng chün* did not wish to have his books copied by others too soon. Permission had to be obtained. Even when a book was borrowed for a long time, no one dared secretly to copy a single character. *Chêng chün* was at first a great Confucianist scholar. He took to *tao* late in life. However, he never stopped teaching *Li chi* 禮記 (Book of Rites) and *Shang shu* 尙書 (Book of History). He was a man of lofty spirit and of dignity. All who saw him would be respectful toward him. When I had a question, I waited until he was cheerful; I dared not ask any question recklessly. Sometimes I had a book in hand for a month, which was time enough for me to copy (a number of pages), but I dared not copy it by stealth, for *Chêng chün* was quick; if by accident he should know it, then his favor (confidence) would be lost, and that would be a great loss for a small gain. I asked for (permission to copy) books by seizing the opportunity. Therefore it was like drinking water beside a river without the possibility of filling the belly with it. However, among his fifty and odd disciples, only I received the books on *chin* and *tan*, *San huang nei wên* 三皇内文, and *Chên chung wu hsing chi* 枕中五行記. Some of the other disciples were not able even to see the titles of these books!

189.) In the first year of the reign of *T'ai-an* (302 A. D.), . . . with his immediate disciples he went eastward to Mt. *Ho* (Anhui Province). I do not know exactly where.

Inner Chapter XX. CLEARING UP ALL DOUBTS.

190.) If one follows an improper teacher to learn *tao*, and in the hope of still learning something, hesitates to leave him, he will accomplish nothing by staying. He wastes his time and his energy in vain. If he repents bitterly, it will be already too late!

191.) Many evil *tao shih* who boast of being *hsien*, who tell many false stories, and who cheat people in order to get their money, are described and discredited. It is because of such as these that people in general do not believe in the existence of *hsien*.

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Manson Benedict, and B. Edwin Blaisdell

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1. Introduction

The investigation of the properties of gases by means of gas thermometers during the first half of the nineteenth century led to the particular form of the absolute temperature scale proposed by Kelvin. At the present time the gas thermometer is recognized as the primary instrument for the determination of temperatures on the absolute scale. Two types of gas thermometer are in general use: the constant pressure instrument in which the pressure of a definite mass of gas is maintained constant and the volume of the system measured at each temperature; and the constant volume instrument in which the volume of a definite mass of gas is maintained constant and the pressure measured at each temperature. In a later paper are given the relations between the measured volumes (or pressures) and the absolute temperature for an idealized gas thermometer filled with an ideal gas; and the corrections to be applied to the observations due to the deviations of the actual from the idealized instrument and of the real thermometric fluid from an ideal gas.

The experimental difficulties encountered in gas thermometric measurements led to the adoption in 1927[1] of an International Temperature Scale which in the temperature range − 190° to + 660° C. is based on the indications of a standard platinum resistance thermometer, an instrument of high precision and reproducibility. Although the International Scale was designed to agree as closely as possible with the absolute scale, the actual deviations in the region above 0° C. are not known with any great degree of certainty.

We have constructed gas thermometers of the constant volume type for the realization of the absolute temperature scale and standard platinum resistance thermometers for reproducing the International Scale and have compared these two scales from 0° to 450° C. The apparatus, methods of calibration, and procedure used in taking the readings are described in the present paper. Our gas thermometers are the same in general design as those used by other investigators[2] with some modifications and improve-

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[1] See G. K. Burgess, Bur. Standards, J. Research, **1,** 635–640 (1928).

[2] P. Chappuis, Trav. et Mém., Bureau Int., **6,** 125 + 187 pp. (1888); ibid., **13,** 66 pp. (1907); ibid., **16,** 44 pp. (1917); P. Chappuis and J. A. Harker, ibid., **12,** 90 pp. (1902); Phil. Trans. Royal Soc. London, **194A,** 37–134 (1900).

L. Holborn and A. L. Day, Am. J. Sci., (4) **8,** 165–193 (1899); ibid., (4) **10,** 171–206 (1900); Wied. Ann. der Physik, **68,** 817–852 (1899); Ann. der Physik, (4) **2,** 505–545 (1900); L. Holborn and S. Valentiner, Ann. der Physik, (4) **22,** 1–48 (1907); L. Holborn and F. Henning, ibid., (4) **35,** 761–774 (1911); F. Henning and W. Heuse, Zeit. f. Physik, **5,** 285–314 (1921); ibid., **6,** ments which, we believe, permit the necessary corrections to be made with greater certainty than heretofore.

2. DESCRIPTION OF THE APPARATUS

(*a*) *General*

A sketch of the apparatus is shown in Fig. 1. The entire system was constructed in duplicate, the individual systems being designated Red and Green for easy identification. There are three pressure systems to be considered: the main thermometer system, the auxiliary thermometer system, and the external pressure control system.

The gas thermometer bulb *B* of vitreous silica was connected through a graded seal to a pyrex glass capillary *A'*. To the top of *A'* was soldered a stainless steel capillary *D* which led to a steel T-valve *F*, used for evacuation of the system and introduction of pure nitrogen, and thence to the short arm *G* of the main mercury manometer *H*. The two arms *G* and *J* of the manometer, the mercury reservoir *L*, and the mercury injector *I* (used for fine adjustment of the mercury levels in the manometer) were connected with each other in a steel block, the various parts of the system being separated by steel stopcocks as shown. The manometer was enclosed in an aluminum housing which was in turn surrounded by an air thermostat *K*. Mercury levels were read to 0.001 mm. by means of a comparator and scale. The gas pressure in the system was adjusted to approximately 1000, 750, 600, 450, or 330 mm. of mercury when the bulb *B* was at 0° C.

The dead space correction for the region of large thermal gradient (the pyrex capillary *A'*) was evaluated by use of the auxiliary gas thermometer[3] *A*, a pyrex glass tube placed parallel to and close beside *A'*. The auxiliary thermometer bulb was sealed to short lengths of glass capillary at the top and bottom. To the top was soldered the stainless steel capillary *C* which led to the short arm *P* of the auxiliary mercury manometer *M*. This system was evacuated, and pure nitrogen introduced through an outlet sealed to the short arm. The two arms *P* and *Q* of the manometer, the mercury reservoir *T*, and the mercury injector *R* were connected with each other in a steel block through steel stopcocks as shown. This manometer was enclosed in a steel housing but was not especially thermostated. Mercury levels were read to 0.1 mm. by means of a slider and scale *S*. The gas pressure in the system was adjusted to approximately 600 mm. of mercury when the bulb *A* was at 0° C.

The gas thermometer bulb *B* and capillary *A'*, and the auxiliary thermometer bulb *A* were enclosed in welded steel cases connected at the top by the steel capillary *E* which led to the open mercury manometer *N*. Levels in this manometer were read to 1 mm. The external pressure control system was filled with dried commercial nitrogen and the pressure adjusted at each measurement to within 3 mm. of the pressure inside the bulb *B*.

(*b*) *Main Thermometer System*

Bulb, Capillaries, and T-Valve. The thermometer bulb *B* was made of vitreous silica by the General Electric Company and was exceptionally clear and uniform in dimensions. The bulb was a right circular cylinder 4 cm. in radius and 15 cm. long capped by two hemispheres of 4 cm. radius, the wall thickness being 2 mm. and the internal volume 1000 ml. A vitreous silica capillary 0.75 mm. bore and 4 cm. long was sealed to

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215–223 (1921); W. Heuse and J. Otto, Ann. der Physik, (5) **2,** 1012–1030 (1929).

H. K. Onnes and coworkers, Physical Lab., Univ. of Leiden, Comm. Nos. **27,** 38 pp. (1896); **60,** 30 pp. (1900); **95e,** 55–67 (1906); **141a,** 1–11 (1914); **152a,** 1–17 (1917); **156a,** 1–32 (1922); **176d,** 43–52 (1925); W. H. Keesom and Miss H. van der Horst, ibid., Comm. No. **188a,** 1–15 (1927); W. H. Keesom, Miss H. van der Horst, and K. W. Taconis, Kamerlingh Onnes Lab., Univ. of Leiden, Comm. No. **230d,** 9 pp. (1933–4).

H. L. Callendar and E. H. Griffiths, Phil. Trans. Royal Soc. London, **182A,** 119–157 (1891); M. W. Travers, G. Senter, and A. Jaquerod, ibid., **200A,** 105–180 (1903); J. A. Harker, ibid, **203A,** 343–384 (1904); N. Eumorfopoulos, Proc. Royal Soc. London, **81A,** 339–362 (1908); ibid., **90A,** 189–203 (1914).

A. L. Day and J. K. Clement, Am. J. Sci., (4) **26,** 405–463 (1908); A. L. Day, R. B. Sosman, and E. T. Allen, ibid., (4) **29,** 93–161 (1910); Carnegie Institution Publication No. **157** (1911); A. L. Day and R. B. Sosman, J. de Physique (5) **2,** 727–749, 831–844, 899–911 (1912).

F. G. Keyes, B. Townshend, and L. H. Young, J. Math. Phys., Mass. Inst. Tech., **1,** 243–312 (1922).

M. Kinoshita and J. Oishi, Phil. Mag., (7) **24,** 52–62 (1937).

[3] N. Eumorfopoulos, Proc. Royal Soc. London, **81A,** 339–362 (1908) for constant pressure gas thermometer; H. K. Onnes and G. Holst, Physical Lab., Univ. of Leiden, Comm. No. **141** (**a**), 1–11 (1914) auxiliary gas thermometer credited to P. Chappuis in this publication; F. Henning, *Temperaturmessung*, p. 47, F. Vieweg und Sohn, Braunschweig, 1915; P. Chappuis, Trav. et Mém., Bureau Int., **16,** 44 pp. (1917).

each end of the bulb. The graded seal was of capillary tubing 0.75 mm. bore at each end but of larger bore for a distance of about 1 cm. where the intermediate glasses were used. The pyrex capillary *A′* was 0.75 mm. bore and 45 cm. long, and was selected from several for uniformity of bore. The stainless steel capillaries *D* were 0.6 mm. bore, the shorter length (*A′* to *F*) being 30 cm. and the longer (*F* to *G*) 300 cm. in length.

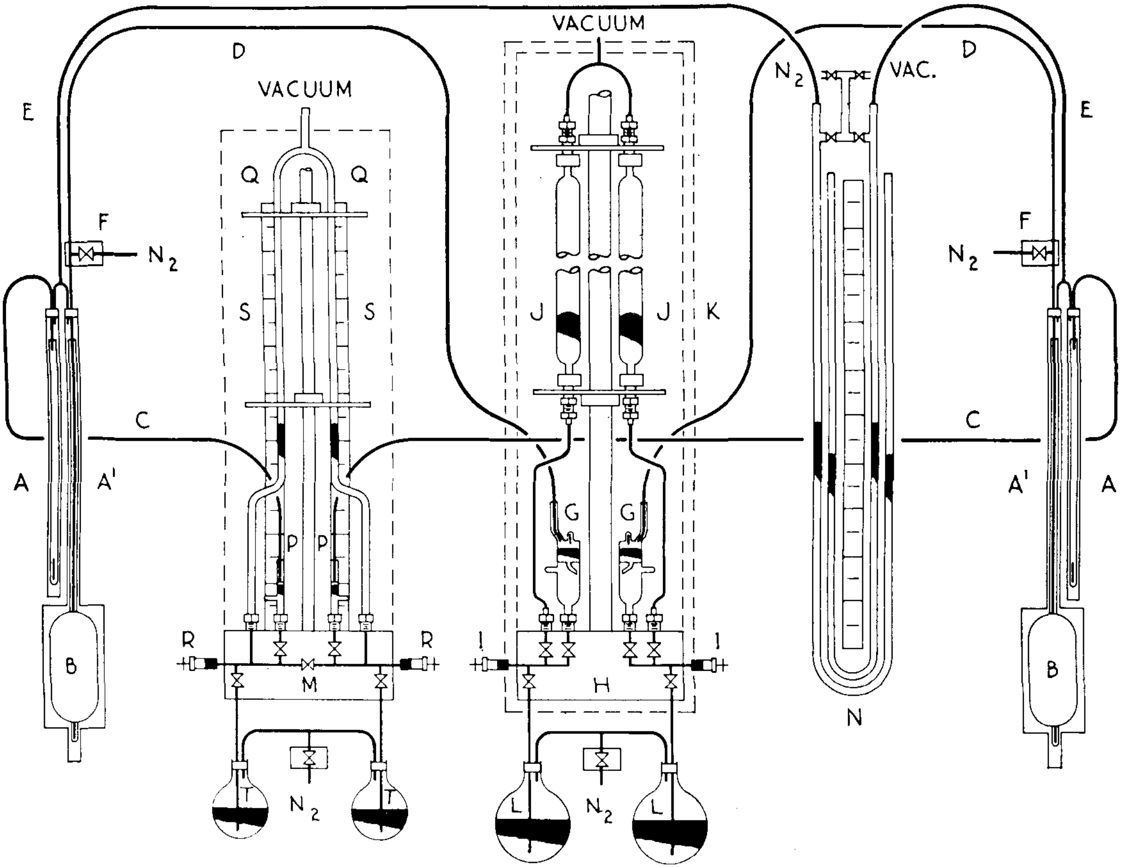

Fig. 1. Sketch of the gas thermometer system.

The glass-to-metal joint at the top of *A′* was made as shown in Fig. 2. The end of the glass capillary was ground perpendicular to the axis of the tube, platinized, and copper-plated. The stainless steel capillary was turned square, coated with silver solder, and tinned. A brass cap which fitted tightly on the steel capillary and was 0.1 mm. in diameter larger than the glass capillary was made. The parts were fitted together and placed with the glass tube pointing upward, a piece of piano wire was thrust through the bore of the steel capillary until it protruded into the glass tube, and solder allowed to run in at *A* with gentle warming until it showed at *B*. The steel capillary was forced against the end of the glass capillary so that contact was made. Attainment of contact was determined by measurement of the distance between index marks on the steel and glass capillaries. A study of test samples showed that solder filled all of the space between the cap and the capillaries and did not run into either tube.

The T-valve is shown in Fig. 2. The stainless steel capillaries *A′* and *G* (which led to the pyrex capillary and to the short arm of the manometer, respectively) were a tight fit in the recessed holes of the T-valve, and their ends were turned off at the same angle as that of the point of the drill used to recess the holes. The joint was soldered with silver solder. That the capillaries were seated in the holes was shown by measurement of

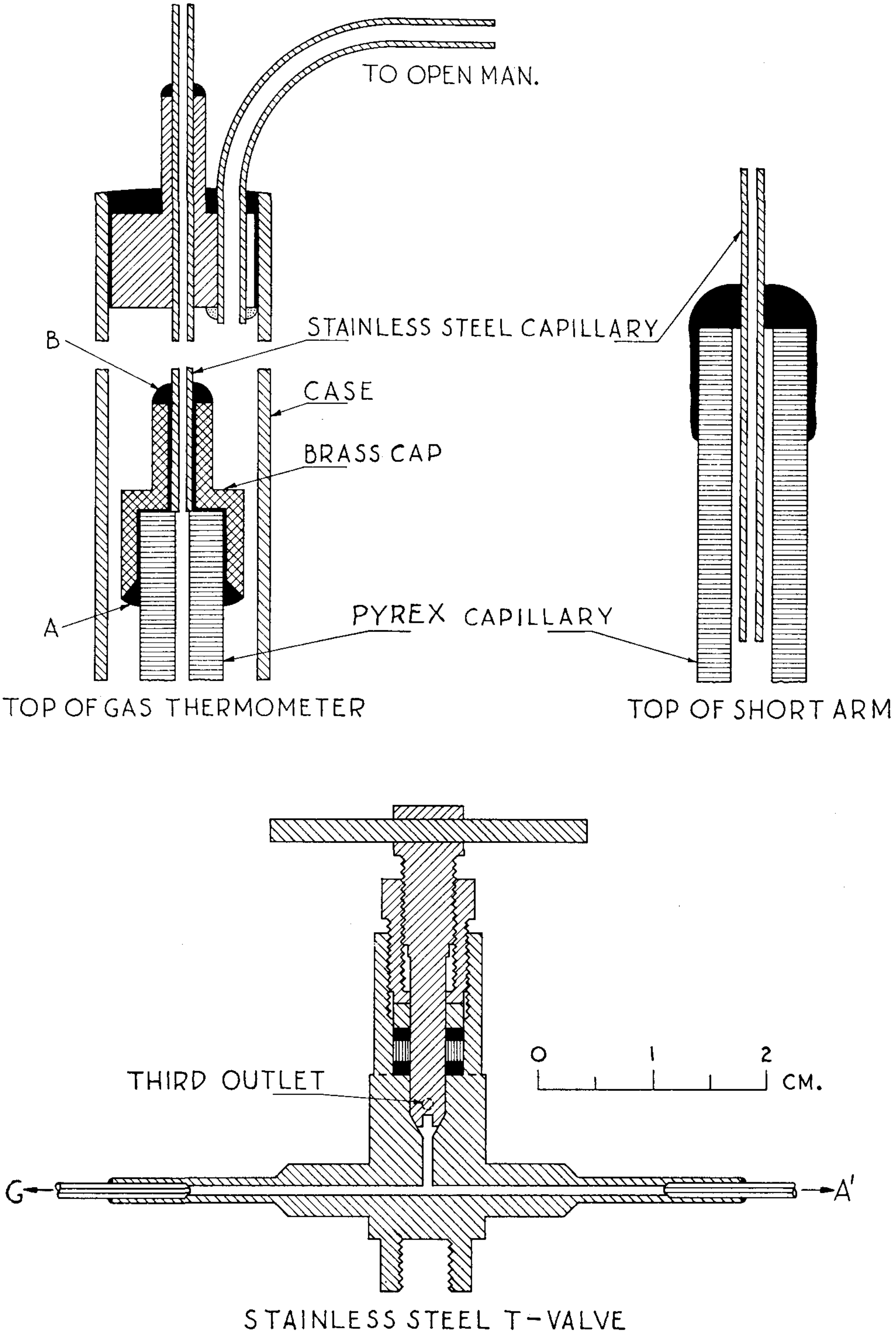
TO OPEN MAN.
STAINLESS STEEL CAPILLARY
B
CASE
BRASS CAP
A
PYREX CAPILLARY
TOP OF GAS THERMOMETER
TOP OF SHORT ARM
THIRD OUTLET
0
1
2
CM.
G
A'
STAINLESS STEEL T-VALVE

FIG. 2. Sketches of the glass-to-metal joints and the T-valve.

the distance between index marks on the capillaries and the T-valve. When the T-valve was open the gas thermometer system was in communication with the loading and evacuation system through a steel tube of 2 mm. bore soldered to the third outlet of the T-valve; when the valve was closed the gas was confined in an all steel system, no packing being exposed to the thermometric fluid.

The glass-to-metal joint at the short arm of the manometer is also shown in Fig. 2. The glass capillary was prepared as described above and the steel capillary tinned at the place where the joint was to come. The steel capillary was inserted in the glass capillary and solder flowed on with gentle warming. No solder flowed into the glass capillary.

Storage, Loading, and Evacuation System. This system, which was built in duplicate, one for each gas thermometer, is sketched in Fig. 3. The gas was stored at a pressure of one meter of mercury in the 5-liter pyrex glass bulb *A*, and was transferred to the main thermometer system by means of the mercury displacement pump *C* made of pyrex glass. Adjustment of the pressure of nitrogen in the reservoir *D* caused the mercury level in *C* to rise or fall. The storage vessel *A*, the displacement pump *C*, a mercury diffusion pump, and the steel tube from the T-valve *F* (Fig. 1) of the main thermometer system were connected with each other in the steel block *B* through steel stopcocks as shown.

Main Manometer. A sketch of the main manometer is shown in Fig. 1. The manometer arms were made of pyrex glass 21 mm. internal diameter and 1.5 mm. wall thickness.

The short arm was 10 cm. long. The closure at the top of the short arm was made by sealing off the tube and attaching without blowing two capillaries: a short capillary in the axis of the tube into which was sealed a tungsten needle 1 mm. in diameter tapered at its lower end and ground flat to a circular surface 0.5 mm. in diameter, and a larger capillary 1.8 mm. bore and 10 cm. long into which was soldered the stainless steel capillary *D* from the thermometer bulb. To the bottom of the short arm was sealed a tube 5 mm. in diameter cemented by DeKhotinsky cement into a steel nut screwed into the valve block *H*. The short arm contained a side-arm for calibration purposes and a trap constructed as shown, which was designed to prevent gas or specks of foreign material from entering the upper chamber. The axis of the short arm was made vertical to within 0.2 mm. per 10 cm. of length.

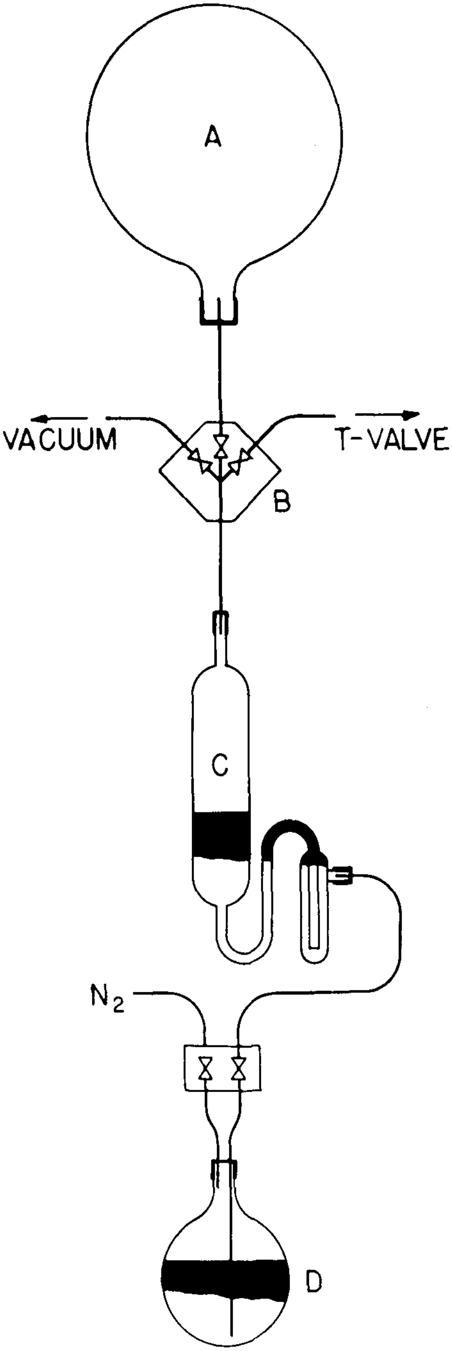

FIG. 3. Storage, loading, and evacuation system.

The long arm was 1.7 meters long and was especially selected after testing many tubes for straightness, uniformity of bore, and freedom from optical imperfections. It was sealed at the top and bottom to tubes 5 mm. in diameter which were cemented into steel couplings, the lower being connected to the valve block by a steel capillary, and the upper to a mercury diffusion pump and McLeod gauge by copper tubes of 5 mm. bore. The axis of the long arm was made vertical to within 0.2 mm. per meter of length and in line with the axis of the short arm by adjustable clamps attached to a ground steel rod 2.5 cm. in diameter and 2.3 meters long. The bottom of the steel rod fitted into the valve block and the top was held by an adjustable pivot attached to the manometer housing. The long arms, which were slightly bowed, were placed so that the curvature was in the plane perpendicular to the line of sight of the telescopes.

The valve block H was of steel. The various parts of the manometer system were attached to the block by means of steel cones, connected inside the block by 0.5 mm. diameter holes, and separated by steel stopcocks similar to that in the T-valve,[4] Fig. 2. The valve block was mounted on a ball bearing turn table and base which permitted a rotation of the whole block as well as a forward and backward motion. The base was bolted to a slate block 50 by 50 by 15 cm. fitted with leveling screws; and the block rested on a steel frame work bolted to the floor. After the system had been adjusted so that all manometer tubes were the same distance from the telescopes, no further changes were made throughout the entire series of measurements.

A cast aluminum-alloy housing enclosing the manometer tubes was bolted to the valve block and held at the top by an adjustable pivot attached to a metal framework bolted to the concrete ceiling. The front and back of the housing were open. The front opening was closed by a plate glass window 1 cm. thick which was pressed gently against thin rubber gaskets glued to the machined surfaces of the housing by means of brass strips held by clamps fastened to the housing; the back was not closed. The front window was vertical to within 0.2 mm. per meter of length.

The temperatures of the mercury in the manometer and of the dead space inside the housing were determined from the readings of five short 12 ohm platinum resistance thermometers enclosed in test tubes filled with mercury and placed alternately on the right and left sides of the housing. Each thermometer was considered to read the temperature of the mercury from a point midway between it and the next lower thermometer to a point midway between it and the next higher one. The lowest thermometer was at the level of the top of the short arm and read the temperature of the short arm dead space.

The valve block and housing were enclosed in an air thermostat K, Fig. 1, made of 1 cm. plywood lined with 2.5 cm. of insulation. Air circulation was maintained by two fans which blew air upwards behind a false back placed 15 cm. in front of the true back and extending to within 30 cm. of the top and bottom. The fans were operated by a motor outside the thermostat and the entire unit rested on an anti-vibration mounting and did not come into contact with the air thermostat box at any place. The air passed upwards behind the false back by a cooling coil through which water from a constant feed device could be circulated, a heating coil, and a mercury-in-steel regulator containing 350 cc. of mercury; and then passed downward in front of the false back around the manometer housing. The mercury levels were viewed through movable slits 1.5 cm. high in the front of the air thermostat box. The slits were not closed by glass when the mercury levels were being measured.

The room in which the apparatus stood was thermostated, and the air stirred by a blower which drew air from the bottom of the room and delivered it to the top.

The mercury used in the manometer system was purified by electrolysis in a dilute solution of nitric acid followed by three distillations: two in a current of air and one in vacuo. It was stored in the glass flask L, Fig. 1, which was connected to the valve block by means of a steel capillary. The storage flask was a barometric height below the short arm of the manometer, and the mercury was forced into the manometer to the desired height by nitrogen pressure. Fine adjustments in mercury height were made by use of the steel mercury injector I, Fig. 1, which had a volume of 10 cc., and a piston diameter of 8 mm. The injector had an indexed head divided into 100 parts.

Illumination. For the determination of the elevation of the crown of a mercury meniscus, a beam of light[5] that behaved as parallel light with respect to vertical displacement and variation in zenith angle and as diffuse light with respect to lateral displacement and variation in azimuthal angle was directed from behind the manometer tube into the telescope of the comparator. The optical system, Fig. 4, consisted of a 6-volt flashlight bulb, a rectangular slit 0.75 mm. high by 2.5 cm. wide covered with a sheet of thin paper and at the principal focus of a cylindrical lens of 5 cm. focal length placed with the elements of the cylinder horizontal, and two rectangular apertures: one 6 mm. high by 2.5 cm. wide between the slit and the lens, and one (the exit pupil) 3 mm. high by 2.5 cm. wide in front of the lens. The system was enclosed in a brass box painted flat black on the inside. The mount carrying the lens could be moved along the long axis of the box and the distance from the lens to the slit was adjusted so that the beam of light was 3 mm. high at 1 meter distance from the front of the box. The box was fastened to a carriage mentioned below and so tilted that the beam sloped upwards toward the telescope at an angle of about 10 minutes to the horizontal. This was accomplished as follows: the telescope was leveled, the horizontal hair-line set on the axis of the telescope, the telescope itself moved so that intersection of the horizontal and vertical hairlines rested on the crown of the meniscus, and the zenith angle of the beam varied until the shadow of the crown on a white card placed immediately in front of the objective fell about 2 mm. above the axis of the telescope.

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[4] For details of the cone joints and stopcocks, see F. G. Keyes, Proc. Am. Acad. Arts Sci., **68,** 505–564 (1933).

[5] S. C. Collins and B. E. Blaisdell, Rev. Sci. Instr., **7,** 213–214, 359 (1936).

The two optical systems, one for each manometer, were rigidly attached to a carriage moving on two vertical drill rods 2 cm. in diameter placed 7.5 cm. behind the back of the aluminum housing but inside the air thermostat. A counterweight attached to the carriage by a cord passing over pulleys fastened to the ceiling of the room permitted the observer to move the optical system so as to illuminate the meniscus in either the long or the short arm of a manometer. In Fig. 4 the carriage and one optical system is shown.

The vertical height of the beam of light could be decreased farther by brass shields painted flat black and shaped to fit the back half of the manometer tubes. Each shield was 7.5 cm. long. It had an apron 0.5 cm. wide along each vertical edge and a slot 1 cm. square in the bottom which permitted light to pass through the central portion of the manometer tube only (see Fig. 4). The shields were connected to counterweights similar to those for the optical systems except that each shield had a separate counterweight.

For the determination of the elevation of the bottom of the meniscus, diffuse light coming from in front of the manometer tubes was used. The optical system consisted of a 6-volt flashlight bulb enclosed in a small metal box with the side facing the manometer tubes consisting of a frosted glass window 2 cm. high by 1 cm. wide. The window was placed with its vertical center-line symmetrical with respect to the axes of the two manometers and at a distance of 16 cm. in

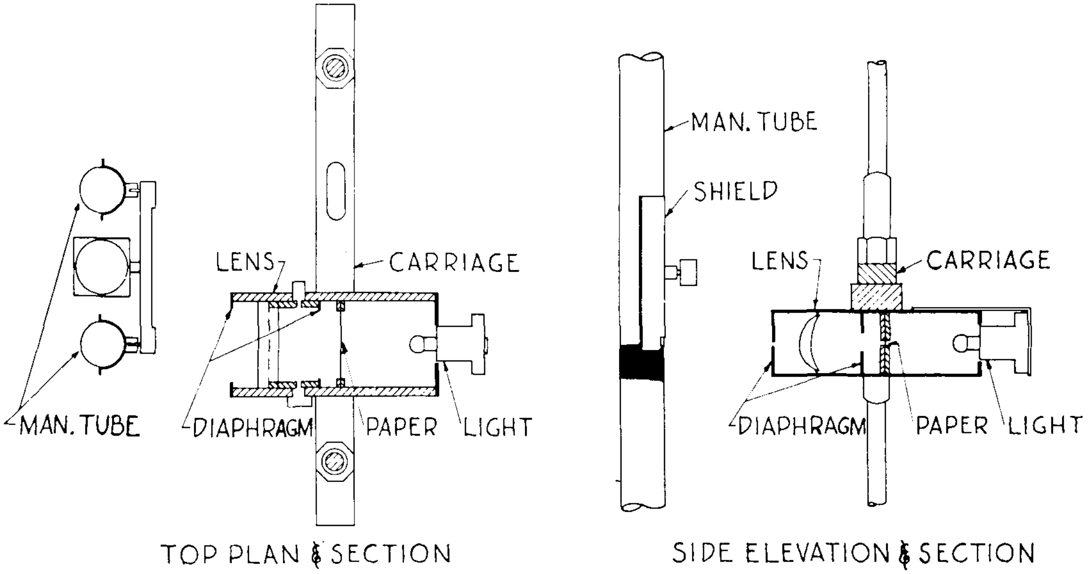

FIG. 4. Optical train for illumination of the mercury meniscus.

front of each axis. The box was rigidly attached to the mechanism that operated the movable slit (in the front of the air thermostat) and the horizontal centerlines of the window and slit were at the same elevations, the optical system and slit moving up and down together. There were two such lighting systems: one for the two long arms and one for the two short arms of the manometers. At each measurement the horizontal centerline of the window and the axis of the telescope were approximately in the same horizontal plane as the crown of the mercury meniscus.

The room was darkened for all measurements. All lamps for illumination of the menisci were turned off except when necessary for an observation.

Comparator and Scale. The two-meter Société Genevoise comparator had an invar bar to which the two telescope carriages could be rigidly clamped by means of split collars and tightening screws. One turn of the micrometer drum of the filar eye-piece of the telescope corresponded to 1 ± 0.001 mm. on the scale. The drum was divided into 100 parts. The two-meter scale was graduated into fifths of millimeters.

The comparator and scale hung from universal joints and were held at the bottom in adjustable bearings, the suspensions being attached to heavy H-beams. The bottoms of the H-beams were bolted to slate blocks fitted with leveling screws and the tops connected to the steel framework, mentioned earlier, by an adjustable pivot. The bar of the comparator and the scale were not out of the vertical by as much as 0.2 mm. per meter of length. The scale was the same optical distance from the telescopes as the axes of the manometer tubes, about 62 cm.

The scale was illuminated by spotlights, attached one to each telescope carriage. The temperature of the scale was measured by a mercury thermometer suspended at the midpoint.

Measurement of Dead Space Temperatures. The temperatures of the stainless steel capillary D and the T-valve were measured by means of four mercury thermometers.

(c) *Auxiliary Thermometer System*

Bulb and Capillary. The auxiliary thermometer bulb A, Fig. 1, was a pyrex glass tube 5 mm. bore by 45 cm. long with a short length of capillary tubing 0.5 mm. bore sealed to each end. The lower capillary was sealed off and the upper one soldered by the same method used for the main thermometer to a stainless steel capillary C, 0.6 mm. bore and 2 meters long, which led to the short arm P of the auxiliary manometer M. The bulb A was selected from several five foot lengths of glass tubes after calibration, and fulfilled the condition that the ratio of the area of the pyrex capillary A' to that of the bulb A in each horizontal plane was constant to within ± 0.5%. The elimination of the error introduced by this variation is taken up in a later paper.

The glass-to-metal joint at the short arm of the manometer was similar to that in the main manometer system.

Loading and Evacuation System. The system was evacuated through a glass tube sealed to the short arm of the manometer. This tube could be brought into communication with the auxiliary thermometer system by lowering the mercury level in the short arm. A two-way glass stopcock connected the system to a mercury diffusion pump or to a supply of commercial nitrogen which had been passed through a liquid air trap.

Auxiliary Manometer. A sketch of the auxiliary manometer is shown in Fig. 1. The manometer arms were of pyrex tubing 5 mm. bore. To the top of the short arm P was sealed a 10 cm. length of capillary 0.3 mm. bore which was sealed at its top to a 1 cm. length of capillary 1.8 mm. bore to receive the end of the stainless steel capillary C. The bottom of the short arm was cemented into a nut screwed into the valve block. Near the top of the short arm was an index mark completely encircling the tube to which the crown of the meniscus was brought in all measurements.

The long arm Q was selected for straightness, uniformity of bore and freedom from optical defects. Its axis was made vertical over the working range and in line with the axis of the short arm by adjustable clamps attached to a central steel rod.

The valve block and manometer housing were similar in construction to those of the main manometer. Since mercury heights were to be read to only 0.1 mm. the front was not closed by a glass plate and the temperature of the mercury was determined by a mercury thermometer placed inside the housing.

Mercury heights were read on a meter stick attached to the central steel rod. A slider having a fine hair-line and a device for eliminating parallax moved on the meter stick and permitted reproducible reading of the crown of the meniscus to 0.1 mm. Diffuse light was used for illuminating the mercury meniscus. The determination of the capillary depression correction is described in a later section.

The mercury storage vessel T and the mercury injector R were similar to those for the main manometer.

Measurement of Dead Space Temperatures. The temperature of the capillary C was measured by means of a mercury thermometer.

(*d*) *External Pressure Control System*

This system eliminates the strain of the thermometer bulbs caused by large differences between the internal and external pressure and also prevents possible diffusion of gas through the bulbs. The main thermometer bulb, pyrex capillary and short length of stainless steel capillary as well as the auxiliary thermometer bulb and a short length of its capillary were enclosed in welded steel cases shown in Fig. 1. Each case was closed at the top, where the steel capillary passed through, by a brass plug and soft solder as indicated in Fig. 2. The auxiliary thermometer case was placed parallel and close to the stem of the main thermometer case. The two cases of one thermometer system were connected at the top by a steel capillary E which led to an open manometer N shown in Fig. 1. This system was filled with dried commercial nitrogen and the pressure adjusted at each measurement to within 3 mm. of the pressure in the main thermometer system. The pressure in the external system was read to 1 mm. of mercury.

The pyrex capillary A', Fig. 1, and the auxiliary thermometer bulb A were wrapped at two places with sufficient asbestos cord to make a tight fit in the steel tubes of the cases.

The gas thermometer bulb B was supported by two large soft springs, one resting on the bottom of the metal case and one on the top. These kept the bulb centered in the case and allowed for differences in thermal expansion between the pyrex capillary A' and the metal tube surrounding it.

(*e*) *Platinum Resistance Thermometers*

Construction. Three types of standard platinum resistance thermometers were made: the Callender mica-cross type and the Bureau of Standards strain-free type were used to realize the International Temperature Scale; the calorimetric or flat type was used for regulation of the thermostat temperature. The methods of construction have been described.[6] All thermometers were of the four-lead potential type and had ice-point resistances of about 25 ohms.

Annealing. Before the platinum wires were wound on the mica frames they were raised to a dull red temperature for 30 seconds by the passage of an electrical current (200 cm. of 0.1 mm. diameter wire can be connected directly across the 110-volt terminals). For some of the thermometers the heating was carried out in air; for others, in an atmosphere of nitrogen. The exclusion of oxygen seemed to have no effect on the subsequent behavior of the thermometer.

The mica-cross and strain-free windings were enclosed in pyrex glass cases protected by metal tubes and the flat type enclosed in metal cases; and the cases evacuated and filled with nitrogen to two-thirds of an atmosphere. The thermometers were annealed by being immersed in a nitrate bath (as used in the high temperature thermostat) at a temperature of 470° (or 480° C.) for two days, then at 500° C. for one day, and then at 470° (or 480° C.) until annealed. Each day the thermometer was removed from the nitrate bath, immersed in liquid air for 15 minutes, and the ice-point resistance measured. A thermometer was considered satisfactorily annealed when a 22-hour period at 470° C. and 15 minutes in liquid air caused a change in ice-point resistance less than 5×10^{-5} ohms ($5 \times 10^{-4\circ}$ C.). The mica-cross and strain-free thermometers annealed in about 6 days; the flat type did not anneal satisfactorily and was used only as a temperature regulating thermometer.

Bridge, Commutator, and Selector. The Mueller thermometer bridge[7] was made by The Eppley Laboratories, Inc.[8] It was of the oil immersion type and was thermostated at $28 \pm 0.005°$ C. The bridge read directly to 10^{-5} ohms (approximately $10^{-4\circ}$ C. on a 25 ohm thermometer) and a variation of 10^{-5} ohms in the bridge setting caused a deflection of 0.2 to 0.5 mm. of the image of the hair-line on the scale. The ratio arms could be balanced against two built-in 25 ohm coils which could themselves be adjusted to equality. The commutator was built into the bridge and the selector was similar to that described before[6] except that mercury cups were used instead of binding-posts.

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[6] J. A. Beattie, D. D. Jacobus, and J. M. Gaines, Jr., Proc. Am. Acad. Arts Sci., **66,** 167–184 (1930).

[7] E. F. Mueller, Bull. Bur. Standards, **13,** 547–561 (1916–17).

[8] M. Eppley, Rev. Sci. Instr., **3,** 687–711 (1932).

All measurements were made with a battery current of 0.002 ampere through the thermometer coil and 30 seconds after depression of the battery key. The heating effect was measured at each temperature at which the thermometer was used and found to be 0.001° C. at 0° C., 0.0008 at 150°, and 0.0004 at 444.6°.

(*f*) *Thermostats*

Two thermostats were used: one for the range 0° to 150° C. was filled with oil, and the other for 150° to 450° was filled with the eutectic mixture of lithium, sodium, and potassium nitrates. The thermostat vessels[9] and stirring mechanism[10] have been described before. When the oil thermostat was used at 0° C., kerosene was circulated by a pump through copper coils immersed in a salt-ice mixture and then through the large steel coil[9] in the thermostat vessel.

A fan blew air across the top of the thermostat in the direction away from the main manometer.

The method of regulation of the temperature of the thermostats has been previously described.[11]

3. CALIBRATIONS, TESTS, AND PERFORMANCE

(*a*) *Main Thermometer System*

Volumes. The volume of the main thermometer bulb was determined from the mass and density of air-free conductivity water contained at 0° C. and one atmosphere pressure inside and outside. The average deviation of three determinations of the volume of a bulb from the mean was less than 0.3×10^{-6} liter.

The coefficient of linear thermal expansion of the material of the bulb from − 190° to + 450° C. was determined from a ring prepared from one of the bulbs after the completion of all gas thermometer measurements. The ring was given the same heat treatment as that given the bulb.

The stretch of the bulb caused by a difference between inside and outside pressure and the coefficient of cubical compressibility of vitreous silica were determined at 25°, 100°, 200°, and 300° C. by a method described in a later paper.

The bulbs were tested for temperature hysteresis: (1) by determination of the volume at 0° C. before and immediately after heating to 450° C. for one day; (2) by measurement of the thermal dilation of mercury in the bulb as described in a forthcoming paper; (3) by measurement by an interference method of the thermal linear expansion of a ring made from one of the bulbs. All three methods indicate that the bulbs did not assume their equilibrium volume at any temperature within 2 hours after being at a quite different temperature but that after being thermostated 6 hours at any temperature the equilibrium volume had be enreached to within 0.3×10^{-6} liter.

The bulbs were tested for pressure hysteresis at 0° and 444.6° C. by the determination of the corrected gas pressure in the bulb (the pressure in the steel case being the same as that in the bulb), evacuation of the case, refilling the case after six hours with nitrogen to the original pressure, and then redetermining the corrected pressure in the bulb. No pressure hysteresis in the range 0 to 2 atm. was found.

This test also proved that the assembly enclosed in the case was free from leak. In the preliminary evacuation of the main gas thermometer system the pressure was followed for a period of a month for a part of which time the bulbs were at 500° C.

The volume of all vitreous and steel capillaries were originally determined from the mass and density of mercury contained. The area of the pyrex capillary *A′*, Fig. 1, was determined at each centimeter from the length (corrected for the volumes of the menisci at each end), mass, and density of a thread of mercury 2 cm. long, the thread being moved along 1 cm. at a time. The volume of the T-valve was originally computed from the known dimensions.

When the main manometer had been set up, the area of the short arm just below the tip of the tungsten needle and the volume from a plane through the tip of the needle to the top of the glass capillary (at *G*, Fig. 1) were determined by the withdrawal of mercury through a side arm, and also by forcing mercury into the evacuated short arm from the calibrated injector *I*. In these measurements the same method of illumination and reading of the height of the meniscus was employed and the same table of meniscus volumes used as in the gas thermometric runs. The diameter of the long arm of the manometer at various heights was determined by similar methods.

The volumes resulting from the above methods were used in the preliminary reduction of the measurements. For the final computations volumes determined in the following manner were used.

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[9] J. A. Beattie, Rev. Sci. Instr., **2**, 458–465 (1931).

[10] S. C. Collins, Rev. Sci. Instr., **7**, 502 (1936).

[11] J. A. Beattie, Proc. Am. Acad. Arts Sci., **69**, 389–405 (1934).

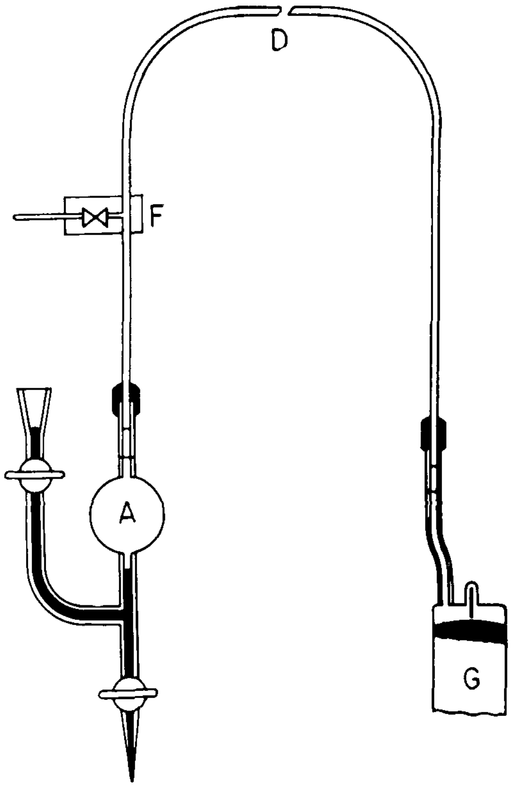

FIG. 5. Gas expansion apparatus for determination of dead space volumes.

After the completion of all of the gas thermometric runs the steel capillary *D*, Fig. 1, was cut just above the soldered joint at the top of *A′* and the volume of the part of the dead space in the steel capillaries, the T-valve, and the short arm of the manometer (that part of the main thermometer system at room temperature) determined in one portion by a gas expansion method.[12] The apparatus is sketched in Fig. 5. A pyrex glass bulb *A*, having a volume about $\sqrt{2}$ times that of the system to be determined, was cemented to the end of the steel capillary. The system was evacuated through the T-valve, the bulb *A* filled with mercury, and nitrogen introduced through the T-valve until the pressure was approximately 1200 mm. The pressure was then read on the main manometer; the mercury was run out of the bulb *A* into a weighing bottle; and the pressure read again. Since the number of moles *N* of nitrogen was the same at both measurements and the temperature was constant to 0.01° C. during a measurement:

$$N = \frac{p_1V_1}{RT + Bp_1} = \frac{p_2(V_1 + \Delta V)}{RT + Bp_2}, \qquad (1)$$

or, if *T* may be considered constant:

$$p_1V_1 = p_2(V_1 + \Delta V) + \frac{Bp_1p_2}{RT}\Delta V, \qquad (2)$$

where

$$V_1 = V_d + V_{s_1} + V_A, \qquad (3)$$

$$\Delta V = (V_{s_2} - V_{s_1}) + V_{Hg}. \qquad (4)$$

Thus

$$V_d = \frac{p_2}{p_1 - p_2}V_{Hg} - V_A + \frac{1}{p_1 - p_2}(V_{s_2}p_2 - V_{s_1}p_1) + \frac{p_1p_2}{p_1 - p_2}\frac{B}{RT}(V_{s_2} - V_{s_1} + V_{Hg}). \qquad (5)$$

In the above relations:

p_1 = initial pressure
p_2 = final pressure
T = Kelvin temperature
B = second virial coefficient for nitrogen at *T*.
V_d = volume of dead space from end of the steel capillary *D* to a horizontal plane through the tungsten tip in the short arm.
V_s = volume in short arm from a horizontal plane through the tungsten tip to the mercury surface (the volume of a cylinder of height equal to the distance from the tungsten tip to the crown of the meniscus plus the covolume of the meniscus). Subscripts 1 and 2 denote this volume in the initial and final measurement, respectively.
V_A = volume in *A* during the initial pressure measurement (the volume of the annular space around the steel capillary plus the volume of a cylinder of height equal to the distance from the end of the steel capillary to the crown of the mercury meniscus plus the covolume of the meniscus).
V_{Hg} = volume of mercury run out of *A*.

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[12] A somewhat similar method was used by L. Holborn and S. Valentiner, Zeit. f. Instr., **28,** 105 (1908); L. Holborn and F. Henning, Ann. der Physik, (4) **35,** 761–774 (1911); A. L. Day and R. B. Sosman, Am. J. Sci., (4) **33,** 517–533 (1912); P. Chappuis, Trav. et Mém., Bureau Int., **16,** 44 pp. (1917); P. G. Cath and H. K. Onnes, Physical Lab., Univ. of Leiden, Comm. No. **152a,** 1–17 (1917).

The steel capillary *D* was then unsoldered from the short arm of the main manometer, and the volume in the short arm itself determined by the gas expansion method outlined above, a short length of calibrated steel capillary being used to connect *A* and the short arm.

The capillary *D* was cut on each side of the T-valve and the volumes of the three parts of the dead space so produced determined in a separate apparatus by a gas expansion method.[13]

Thus the volume of the portion of the dead space at room temperature was determined in three separate experiments: (1) before the gas thermometric runs by the mass and density of mercury contained in the separate parts; (2) after the gas thermometric runs in a single portion by a gas expansion method, and (3) in four portions by a gas expansion method. Method (1) gave too small values of the volumes for all steel parts and correct volumes for glass parts of the apparatus. This effect has been discussed in another publication.[13] For both gas thermometric systems methods (2) and (3) agreed to 5×10^{-6} liter or better. Method (2) was taken to give the correct dead space volume.

The capillary *A′*, Fig. 1, was cut between the bulb *B* and the graded seal and its volume (which included a portion of vitreous silica capillary, the graded seal, the pyrex capillary, the metal to glass joint, and a short portion of steel capillary) determined by a gas expansion method.[13] Since most of this system was of vitreous material, the volume so determined agreed well with that measured before the gas thermometric runs from the mass and density of mercury contained.

Elevations. The methods used for determining the elevations of the crown and bottom of a mercury meniscus were tested for error before and after the gas thermometer measurements. Sources of error investigated were: (1) the scale, (2) the comparator, (3) the plate glass, (4) the manometer tubes, and (5) the lighting system.

The scale was calibrated at the U. S. National Bureau of Standards. Frequently during the measurements the filar micrometers of the comparator were run over all divisions within 2 mm. of those used. This served to check the calibration of the scale and also the thread of the micrometer. Apparent errors greater than 0.002 mm. were never found.

The bar of the comparator was made vertical by sighting with the telescopes on three plumb lines arranged 120° apart. The optical axis of the objective of the telescopes did not coincide exactly with the mechanical axis. Both objectives were turned so that the displacement of the image was in the horizontal plane. The positions of the scale and manometer tubes were carefully adjusted and the objectives of the telescopes focused so that the images of the rulings and crowns of the menisci were in the vertical planes of the hair-lines, and thereafter no changes were made during all runs and calibrations. The eyepieces were refocused on the hair-lines and the telescopes leveled when necessary. The vertical cross-hairs of the telescopes were made parallel with the vertical line on the scale. At various times the elevation of the same mercury surface was read by each of the two telescopes. No systematic difference was found.

The errors due to optical defects in the plate glass front and in the manometer tubes were investigated throughout the runs. Such errors may arise because: (1) the inner and outer walls are parallel but not vertical; and (2) the two walls are not parallel. The error due to the first effect is small and easily calculated: each part of the system was set up so that the error was less than 0.001 mm. The error caused by a wedge in the glass could not be evaluated directly. The effect in the plate glass was proved negligible by measuring the thickness of the glass at various points and by viewing the scale through the plate glass. The effect in the manometer arm both long and short were studied: (1) by measurement of the distance between lines on a scale hung inside the glass tube so as to coincide with the axis of the tube; (2) by measurement of the apparent displacement of the center of a fine wire stretched behind the manometer tube with respect to the ends of the wire, and (3) by measurement of the same pressure (produced in the manostat[14]) with the two manometers. After the gas thermometric runs the tops of the short arms were cut off and a scale inserted with one graduation outside and the other inside the tube at the height of the position of the tungsten tip. The distance between marks (about 1 mm.) was read on the telescope when the scale was directly behind the front wall of the tube and then when the scale was in the axis of the tube. In all of these tests errors as large as 0.005 mm. were seldom found and in general the errors were of the order of 0.003 mm. which was well within the precision of the methods used.

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[13] J. Kaminsky and B. E. Blaisdell, Rev. Sci. Instr., **10,** 57–58 (1939).

[14] J. A. Beattie, M. Benedict, and B. E. Blaisdell, Proc. Am. Acad. Arts Sci., **71,** 327–360 (1937).

A study of the effect of various methods of illumination of the crown and bottom of a meniscus on the apparent elevations will be presented in a forthcoming paper. The method of illumination of the crown described in a previous section of the present paper is the most satisfactory investigated. An experienced observer could read the elevation of the crown with this method of lighting with a probable error of a single observation of 0.001 mm. (5 readings). The apparent elevation was independent of: (1) the relative elevation of the axis of the telescope and the crown provided the image of the crown could be seen, (2) vertical displacement and variation in zenith angle of the optical system provided the beam of light did not slope downward to the telescope, (3) lateral displacement and variation in azimuthal angle of the optical system, (4) height of the bottom of the shield above the crown or indeed whether or not a shield was used, and (5) interchange of the two optical systems.

With the method of illumination of the bottom of the meniscus used, the height of the meniscus could be read with a probable error of 0.005 mm. (5 observations) provided the elevation of the telescope was not changed. However, as will be discussed in a later paper, the apparent elevation of the bottom (and hence height of the meniscus) determined by this method of reading is a linear function of the vertical distance from the axis of the telescope to the horizontal plane determined by the bottom of the meniscus. In our measurements this distance was 1.8 ± 0.1 mm. for the short arms of the manometers and 1.2 ± 0.5 mm. for the long arms. The measured heights of menisci in the short arm were about 1.8 mm. and were too large by 0.033 ± 0.002 mm.; those in the long arm were about 1.2 mm. and were too large by 0.024 ± 0.008 mm. The corresponding correction to the capillary depression correction in the short arm is $-$ 0.0005 ± 0.0000 mm. and that in the long arm $-$ 0.0005 ± 0.0002 mm. so that the net systematic error in capillary depression correction caused by the method of reading menisci heights is 0.0000 ± 0.0002 mm. The correction to the meniscus covolume in the short arm is $-(2.3 \pm 0.1) \times 10^{-3}$ ml. Since the same method of illumination was used for the calibration of dead space volumes as for the gas thermometric measurements the systematic error 2.3×10^{-3} ml. cancels leaving as a random error 0.1×10^{-3} ml.

Temperatures. All mercury thermometers were calibrated in the range used against platinum resistance thermometers.

The temperature of the room varied about 0.2° C. from floor to ceiling and remained constant to about 0.1° C. during a run. The short length of steel capillary and T-valve were directly over the top of the thermostat and the temperature of these parts of the dead space was about 2° C. higher than those further removed from the bath for the high temperature runs.

The air thermostat surrounding the mercury column was maintained at a temperature 1° to 2° C. higher than that of the room. Inside the aluminum housing the temperature from top to bottom varied about 0.02° C. and remained constant to 0.01° C. during a run. In most of the runs temperature conditions were better than those described above; in a few they were worse.

Surface Tension of Mercury. Keesom, van der Horst, and Taconis[15] determined the volumes of mercury menisci from X-ray shadowgraphs of the menisci taken at each measurement. We computed the capillary depression and volumes of menisci from the diameter of the tube, height of the meniscus, and the capillary constant of mercury. The latter was determined from X-ray shadowgraphs of the menisci in both short arms and both long arms of the manometer after the completion of the gas thermometer runs. Photographs were taken for several positions of the menisci and for several meniscus heights in all tubes. The x and y coordinates were measured on an astronomical plate-measuring machine at the Harvard Observatory. Blaisdell[16] has integrated by numerical methods Laplace's equation for the surface of equilibrium of a fluid in a gravitational field for 40 values of the parameter and has prepared tables of the coordinates, capillary depressions, and meniscus volumes. From these tables and the measurements of the shadowgraphs it was possible[17] to determine the capillary constant and hence the surface tension of the mercury in our manometers. The values of the capillary constant a for mercury were 0.268 ± 0.001 cm. and 0.264 ± 0.001 cm. for the two short arms of the manometer at 27° C. The average, 0.266 cm., corresponds to a surface tension of 469 dynes per cm. at 27° C. The capillary constants of the mercury in the long arms were 0.248 ± 0.001 cm. and 0.249 ± 0.001 cm. The lower value was accounted for by the fact that after run No. 379 the mercury in the long arms was fouled because of a leak in the system for evacuation of the long arms.

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[15] W. H. Keesom, Miss H. van der Horst, and K. W. Taconis, Kamerlingh Onnes Lab., Univ. of Leiden, Comm. No. **248a,** 1–5 (1937).

[16] B. E. Blaisdell, J. Math. Phys., M. I. T., **19,** 186–245 (1940).

[17] J. A. Beattie, B. E. Blaisdell, and J. Kaye, Proc. Am. Acad. Arts and Sci., **74,** 389–397 (1941).

(*b*) *Auxiliary Thermometer System*

The dead space volumes of the auxiliary gas thermometer used in the final computations were determined by the gas expansion method. The mean difference between the capillary depression of the mercury in the long and short arm of the manometer was determined in a series of experiments and this correction applied to all readings. No attempt was made to compute the capillary depression, or determine the capillary constant of mercury as was done for the main manometer.

(*c*) *Platinum Resistance Thermometers*

The platinum resistance thermometers were calibrated at the ice, steam, mercury boiling, and sulphur boiling points. The methods of realization of these points and the relations for the effect of pressure on the equilibrium temperature have been published.[18]

The ice point resistance of each thermometer was determined each day. The thermometers were calibrated at the other three fixed points every three months or so. Immediately after calibration the maximum difference from the lowest to the highest reading of the four thermometers was 0.001° C. or less when immersed in the same thermostat. As time went on the readings began to diverge and when the maximum difference became 0.003° C. the thermometers were recalibrated. In general the use of the new α and δ obtained in a calibration did not cause a difference of more than 0.001° C. in the indication of a thermometer from that computed by the α and δ of the preceding calibration.

The agreement of the four thermometers on the value of a given temperature is indicated by the following: in the runs from 0° to 150° C. the mean for all runs (Nos. 111 to 251) of the average deviation of the four thermometers from the mean value in the oil bath was 0.0007° C.; in the runs from 150° to 444.6° C. in the nitrate bath this mean for all runs (Nos. 252–394) was 0.0019° C.

Each morning the balance of the ratio coils of the bridge was tested, adjustment being made if necessary and the "zero balance"[7] of the bridge determined and subtracted from all readings made that day. The N and R readings were each taken with the battery current in the direct and reverse direction.

The short platinum resistance thermometers inside the aluminum housing were calibrated before and after the gas thermometer runs. The constants of the thermometers did not change by amounts great enough to affect their indications by 0.001° C.

The thermometer bridge was calibrated every two years in terms of one of the 100 ohm coils. The corrections changed very little with time and were determined for any month by linear interpolation between calibrations.

(*d*) *Thermostats*

The performance of the thermostats is indicated by the figures given in the preceding section. In general four thermometers after calibration agreed on the temperature of the bath to within ± 0.001° C. and this was checked by placing one thermometer in the four positions occupied by the four thermometers during a run. In the oil bath at 150° C. the agreement was not so good, being ± 0.002° C. This was due to insufficient insulation of the top of the bath; an effect which was eliminated in the nitrate bath.

The temperature of the thermostat did not vary more than 0.002° C. (usually not more than 0.001° C.) during the one hour required for a run.

4. TEST OF THE PERFORMANCE OF THE AUXILIARY THERMOMETER

The theory of the use of the auxiliary thermometer as a means of determining the mean reciprocal temperature of that portion of the dead space in the region of large thermal gradient will be given in a later paper. The requirements to be fulfilled are: (1) the ratio of the area of the capillary A' of the main thermometer system to that of the bulb A of the auxiliary thermometer should be independent of height and of temperature (each tube being at the same temperature); and (2) the temperature of A' should be the same as that of A at each horizontal plane.

The failure of the apparatus to satisfy the first condition exactly can be eliminated when the temperature distribution along A' and A are known. In order to determine this distribution and to determine the errors of all simplifications made in the formulae, the temperature along A' was measured by use of seven thermocouples and the mean reciprocal temperature measured by means of the auxiliary thermometer for thermostat temperatures of 444.6° and 180° C. From a plot of temperature against distance the temperature of A' at the middle of each one-centimeter interval was read off and the dead space correction evaluated as a sum of 45 terms. The corrections were also evaluated from the indications of the auxiliary thermometer. For a thermostat temperature of 444.6° C. and a pressure of 1600 mm. in the bulb of the main thermometer, the error in the dead space correction for the gas in A' obtained by the use of the mean reciprocal temperature indicated by the auxiliary thermometer was 0.003 mm. of mercury; for a bath temperature of 180° C. and a pressure of 1000 mm., the error was 0.0005 mm.

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[18] J. A. Beattie, T.-C. Huang, and M. Benedict, Proc. Am. Acad. Arts Sci., **72,** 137–155 (1938); J. A. Beattie, M. Benedict, B. E. Blaisdell, and J. Kaminsky, ibid., **71,** 327–385 (1937).

5. Filling the Gas Thermometers

Preparation of the Nitrogen. Pure synthetic ammonia was distilled back and forth between two bulbs, the head and tail portions being discarded. After each distillation the ammonia was frozen with liquid air and pumped to a flat gauge. The ammonia vapor was then passed over a catalyst at 500° C. to decompose it into its elements, then over copper oxide at 550° C., traps for removal of water, finely divided nickel at 700° C., and finally through a tube filled with chabazite at − 78° C. The purified nitrogen was finally drawn through a liquid air trap and pumped into the bulb A of the storage system, Fig. 3.

Spectrograms of the nitrogen and of the same gas to which various known amounts of oxygen and hydrogen were added showed that the nitrogen prepared by this method contained less than 0.05 mol percent oxygen and less than 0.05 mol percent hydrogen. Analysis of the gas after the completion of the thermometric measurements gave the same results.

Preparation of the Bulbs. After the thermometric system had been completely assembled, the bulbs were heated to 500° C. and evacuated for two days through the T-valve. The pressure was then 0.009 mm. of mercury 12 hours after pumping was stopped and was increasing at the rate of 0.0002 mm. per hour, the bulbs being at 500° C. The bulbs were then filled with pure nitrogen to a pressure of 1 mm. and the system again evacuated for one week with the bulb at 500° C. This process was repeated two times, so that the bulbs were evacuated for over three weeks while at 500° C.

Loading the Bulbs. In order to adjust the ice point pressure of the thermometer, the bulb was cooled to 0° C., the gas pumped into the system by use of the mercury displacement pump, Fig. 3, until the corrected pressure was within 1 mm. of the desired value and the T-valve closed.

6. Procedure for a Run

General. The two gas thermometers filled with nitrogen to the same ice point pressure and four platinum resistance thermometers were placed in the thermostat, regulated to within a few thousandths of a degree of some even International temperature, and the indications of each instrument measured.

The range from 0° to 150° C. was first investigated, the oil thermostat being used. Readings at 0°, 25°, 50°, 75°, 100°, and 150° C. were taken for most of the ice point pressures of 1000, 750, 600, 450, and 333 mm. of mercury. Many more readings were taken at 0° and 100° C. than at other temperatures. The intermediate temperatures were approached from above and from below. The 150° C. readings were not taken at the 1000 mm. loading.

All the thermometers were then transferred to the nitrate bath. Readings were made at 150°, 200°, 250°, 300°, mercury boiling point, 400°, sulphur boiling point for each of the ice point pressures 600, 450, and 333 mm. of mercury. Most attention was given to the 150° and the sulphur boiling point; the other temperatures were approached from above and below. The corrected pressures in the gas thermometers at 150° C. were adjusted to within 1 mm. of those obtained in the oil thermostat for each ice point pressure. The correct ice point pressures to be associated with a series of runs from 150° to the sulphur boiling point were determined from equations based on the results obtained in the oil thermostat.

Seasoning. It was found that the ice point (or 150° point) pressure would gradually increase when the bulb was heated to the highest and cooled to the lowest temperature many times. This effect was eliminated by heating the bulb filled with nitrogen to the proper ice point pressure to the highest temperature of the complete series of runs (150° C. for the 0° to 150° series and 444.6° C. for the 150° to 444.6° C. series) for about one week. Thereafter the ice point (or 150°

point) pressure remained practically constant, sometimes increasing slightly, sometimes decreasing slightly as the measurements progressed.

Preparation for a Run. On the day before a run the mercury in the long arm of the main manometer was set about 0.1 mm. higher than the expected value, and then the injectors were used to transfer about 2 cc. of mercury from the short arm to the long arm so that the mercury in the short arm would not be in contact with the glass at the working level except during a run. The current in the external heaters of the thermostat was adjusted so that the desired temperature was approximately maintained.

On the morning of the day of a run the balance of the ratio arms and the "zero balance" of the resistance bridge were measured. The temperature of the thermostat was adjusted to within 0.003° C. of the desired International temperature and the regulation switched to the automatic regulating device.

The pumps for maintaining the vacuum in the long arms of the main and auxiliary thermometers were started. The stopcocks in the valve blocks were opened and the levels of mercury adjusted by use of the injectors until the crowns of the menisci in the short arms were 0.1 mm. below the tungsten tip. The pressure in the steel cases surrounding the thermometer bulbs was adjusted.

A run was started only after the temperature of the room and that of the air thermostat surrounding the main manometer had been satisfactorily constant for at least twelve hours; and the temperature regulation of the oil or nitrate thermostat satisfactory for one hour. A run lasted about one hour.

At the end of each day the ice point resistances of the four platinum resistance thermometers were read.

Observations. A run consisted of six sets of readings of: (1) the resistances with the commutator in the direct and reverse position of the four standard platinum resistance thermometers, and of the five short resistance thermometers in the air thermostat; (2) the temperatures of the resistance bridge, steel capillaries, scale, and auxiliary manometer; (3) the barometer, mercury levels in the auxiliary manometer and in the open manometer; and (4) the settings (average of three readings) of the micrometers in the oculars of the telescopes when the cross-hairs were on the crown and on the bottom of the mercury menisci in the long and short arms of the main manometer, the settings on the tungsten tips, and the settings on the scale divisions nearest these positions.

For four of the six sets of readings that composed a run, one experimenter made the observations (1) and a second the observations (2) to (4); for the last two sets the experimenters exchanged positions.

7. Summary

A duplicate constant volume gas thermometer for the realization of the absolute temperature scale from 0° to 450° C. is described. Methods of construction, calibration, and testing are given. The performances of the various units are outlined. The procedure used for comparison of the International Temperature Scale with the absolute scale is given.

(Contribution from the Research Laboratory of Physical Chemistry,
Massachusetts Institute of Technology, No. 454)

AN EXPERIMENTAL STUDY OF THE ABSOLUTE TEMPERATURE SCALE

VII. THE THEORY OF THE CORRECTION OF THE OBSERVATIONS ON GAS THERMOMETERS FOR THE IMPERFECTIONS OF THE APPARATUS AND OF THE THERMOMETRIC FLUID

By James A. Beattie, Manson Benedict, and Joseph Kaye

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1. INTRODUCTION

Two types of gas thermometers—constant volume and constant pressure—are in general use for the realization of the absolute temperature scale. In each the experimental instrument differs from the idealized one in important respects and the real thermometric fluid differs from a perfect one.

In the idealized constant volume (or constant density) gas thermometer a definite mass N of gas is enclosed in a bulb of invariant volume V_0, the density of the gas being constant throughout the bulb. The pressures p_0, p_{100}, and p_t of the gas are measured while the bulb is thermostated at the respective temperatures 0°, 100°, t° C. The mean coefficient α_v of thermal pressure increase at constant volume of the gas from 0° to 100° C., and the Centigrade temperature t_v on the constant volume scale of the gas (corresponding to t° C.), each for the gas density corresponding to a pressure of p_0 at 0° C., are defined by means of the relations:

$$p_{100} = p_0\,(1 + 100\,\alpha_v), \qquad (V = \text{constant};\ N = \text{constant}) \tag{1}$$

$$p_t = p_0\,(1 + \alpha_v\,t_v), \qquad (V = \text{constant};\ N = \text{constant}) \tag{2}$$

where α_v has the same value in both equations. Eq. (1) may be written:

$$p_{100}\,V_{100} = p_0\,V_0\,(1 + 100\,\alpha_v), \qquad (V_{100} = V_0;\ N = \text{constant}) \tag{3}$$

$$\alpha_v = \frac{p_{100} - p_0}{100 p_0} = \frac{p_{100}V_{100} - p_0V_0}{100\,p_0V_0}; \qquad (V_{100} = V_0;\ N = \text{constant}) \tag{4}$$

and Eq. (2) written:

$$p_t\,V_t = p_0\,V_0\,(1 + \alpha_v\,t_v), \qquad (V_t = V_0;\ N = \text{constant}) \tag{5}$$

$$t_v = \frac{p_t - p_0}{\alpha_v\,p_0} = \frac{p_tV_t - p_0V_0}{\alpha_v p_0\,V_0}, \qquad (V_t = V_0;\ N = \text{constant}) \tag{6}$$

$$= 100\,\frac{p_t - p_0}{p_{100} - p_0} = 100\,\frac{p_tV_t - p_0V_0}{p_{100}V_{100} - p_0V_0}. \qquad (V_t = V_{100} = V_0;\ N = \text{constant}) \tag{7}$$

There are two forms of idealized constant pressure gas thermometer. In the first a definite mass N of gas is enclosed in a bulb of variable volume, the pressure being constant throughout the system and having the value p_0. The volumes V_0, V_{100}, and V_t of the bulb are measured when the bulb is thermostated at the respective temperatures 0°, 100°, t° C., the pressure being brought to the value p_0 at each temperature by adjustment of the volume of the bulb. The mean coefficient α_p of thermal dilation at constant pressure of the gas from 0° to 100° C., and the Centigrade temperature t_p on the constant pressure scale of the gas (corresponding to t° C.), each for the gas pressure p_0, are defined by means of the relations:

$$V_{100} = V_0\,(1 + 100\,\alpha_p), \qquad (p = \text{constant};\ N = \text{constant}) \tag{8}$$

$$V_t = V_0\,(1 + \alpha_p\,t_p), \qquad (p = \text{constant};\ N = \text{constant}) \tag{9}$$

where α_p has the same value in both equations. Eq. (8) may be written:

$$p_{100}\,V_{100} = p_0\,V_0\,(1 + 100\,\alpha_p), \qquad (p_{100} = p_0;\ N = \text{constant}) \tag{10}$$

$$\alpha_p = \frac{V_{100} - V_0}{100V_0} = \frac{p_{100}V_{100} - p_0V_0}{100p_0V_0}; \qquad (p_{100} = p_0;\ N = \text{constant}) \tag{11}$$

and Eq. (9) written:

$$p_t\,V_t = p_0\,V_0\,(1 + \alpha_p\,t_p), \qquad (p_t = p_0;\ N = \text{constant}) \tag{12}$$

$$t_p = \frac{V_t - V_0}{\alpha_pV_0} = \frac{p_tV_t - p_0V_0}{\alpha_pp_0V_0}, \qquad (p_t = p_0;\ N = \text{constant}) \tag{13}$$

$$= 100\,\frac{V_t - V_0}{V_{100} - V_0} = 100\,\frac{p_tV_t - p_0V_0}{p_{100}V_{100} - p_0V_0}. \qquad (p_t = p_{100} = p_0;\ N = \text{constant}) \tag{14}$$

In the second form of idealized constant pressure thermometer a definite mass N of gas is enclosed in a bulb of invariant volume V_b connected by a tube of negligible volume to a pipette of variable volume v which is kept at a constant temperature (say 0° C.), the pressure being constant throughout the system and having the value p_0. The method of operation is the same as that described in the preceding paragraph except that the pressure is adjusted to p_0 at each bulb temperature by adjustment of the volume of gas in the pipette. Let v_0, v_{100}, and v_t be the gas volumes in the pipette (at 0° C.) when the bulb temperatures are, respectively, 0°, 100°, t° C. Then:

$$V_b + v_0 = \frac{V_b}{1+100\alpha_p} + v_{100}, \qquad (p = \text{constant};\ N = \text{constant}) \qquad (15)$$

$$V_b + v_0 = \frac{V_b}{1+\alpha_p t_p} + v_t, \qquad (p = \text{constant};\ N = \text{constant}) \qquad (16)$$

where α_p has the same value in both equations. Thus:

$$\alpha_p = \frac{1}{100}\,\frac{v_{100}-v_0}{V_b-(v_{100}-v_0)}, \qquad (p = \text{constant};\ N = \text{constant}) \qquad (17)$$

$$t_p = \frac{1}{\alpha_p}\,\frac{v_t-v_0}{V_b-(v_t-v_0)}. \qquad (p = \text{constant};\ N = \text{constant}) \qquad (18)$$

Let D_0, D_{100}, and D_t be the gas densities in the bulb at the respective temperatures 0°, 100°, t° C. Then

$$N = D_0\,(V_b + v_0).$$

The number of moles of gas in the bulb at 100° and t° C. are, respectively:

$$N_{b100} = D_0\,(V_b + v_0) - D_0\,v_{100},$$

$$N_{bt} = D_0\,(V_b + v_0) - D_0\,v_t;$$

and the densities of the gas *in the bulb* at 100° and t° C. are, respectively:

$$D_{100} = \frac{N_{b100}}{V_b} = D_0\,\frac{V_b-(v_{100}-v_0)}{V_b},$$

$$D_t = \frac{N_{bt}}{V_b} = D_0\,\frac{V_b-(v_t-v_0)}{V_b}.$$

Whence:

$$D_0 = D_{100}\,(1 + 100\,\alpha_p), \qquad (p = \text{constant}) \qquad (19)$$

$$D_0 = D_t\,(1 + \alpha_p\,t_p), \qquad (p = \text{constant}) \qquad (20)$$

where α_p has the same value in both equations; and:

$$\alpha_p = \frac{D_0-D_{100}}{100D_{100}}, \qquad (p = \text{constant}) \qquad (21)$$

$$t_p = \frac{D_0-D_t}{\alpha_p D_t}. \qquad (p = \text{constant}) \qquad (22)$$

In all of the Eqs. (8) to (22) each of the quantities α_p and t_p has the same numerical value for a given pressure p_0 of a given gas. The practical constant pressure gas thermometer corresponds to the second type of idealized instrument described. Eqs. (8) to (14) may however be used, the gas in the pipette being considered as part of the dead space. The method of making the correction for this effect is presented in a later section.

In the experimental constant volume or constant pressure gas thermometer the pressure is measured on a manometer (usually mercury) which is outside of the thermostat surrounding the thermometer bulb and is connected to the bulb by a fine capillary. Thus a part of the system is at a temperature different from that of the bulb (or those of the bulb and pipette); furthermore the walls of the system are strained because of changes in pressure and temperature, and the system is in a gravitational field.

The observed quantities must be corrected for: (1) the imperfections of the manometer system; and (2) the deviation of the practical from the idealized thermometer system. When pressures or volumes so corrected are substituted into the relations given above, there result values of α_v, t_v, α_p, and t_p which depend on the kind of gas used and on the density or pressure of the gas at 0° C., and not on the imperfections of the practical thermometer system.

The general thermodynamic theory of real and perfect gases[1] gives the result that for any gas:

$$\lim_{p_0 \to 0} \alpha_v = \lim_{p_0 \to 0} \alpha_p = \alpha = \frac{1}{T_0}, \tag{23}$$

and

$$\lim_{p_0 \to 0} t_v = \lim_{p_0 \to 0} t_p = t. \tag{24}$$

In these equations α is the thermometric coefficient, α_v or α_p, of an ideal gas:

$$\alpha = \frac{p_{100}V_{100} - p_0V_0}{100\ p_0V_0}, \qquad (p_{100} = p_0 \text{ or } V_{100} = V_0; N = \text{constant})$$

$$= \frac{RT_{100} - RT_0}{100\ RT_0} = \frac{1}{T_0}, \tag{25}$$

and is independent of density; T_0 is the Kelvin temperature of the ice point; and t is thermodynamic temperature on the Centigrade scale, the corresponding Kelvin temperature T being

$$T = t + T_0. \tag{26}$$

The extrapolation to zero ice-point pressure indicated in Eqs. (23) and (24) may be accomplished: (1) by determination of the value of the quantity for several different ice-point pressures and extrapolation to zero pressure by graphical or analytic methods; (2) by determination of the value of the quantity for one or more ice-point pressures and correction for the deviation of the properties of the real from those of the ideal gas by means of (a) compressibility data on the gas or (b) values of the Joule (for α_v and t_v) or Joule-Thomson (for α_p and t_p) coefficients for the gas. Since Joule coefficients are difficult to measure, the values of α_v and t_v may be corrected to zero ice-point pressure from combined measurements of compressibility and of Joule-Thomson coefficients. Method (1) requires only gas thermometric measurements; method (2) requires in addition auxiliary thermodynamic data on the gas used.

The present paper is concerned with the computation of Kelvin temperatures from the observations made with constant volume and constant pressure gas thermometers, and in particular the corrections necessitated by the imperfections of the manometer system, the thermometer system, and the thermometric fluid. In the preceding paper[2] are given a description of a duplicate constant volume gas thermometer and auxiliary equipment, methods of calibration and testing, performance of the apparatus, and the method of taking observations.

2. Reduction of Observed Mercury Heights to Standard Conditions

The corrections to be applied to the observations made on a mercury manometer with a comparator, having two telescopes which can be rigidly clamped to the vertical bar, and a scale are: (1) the scale corrections, and (2) the mercury corrections.

The uncorrected difference H in elevation between the mercury surface in the long arm and in the short arm of the manometer is

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[1] J. A. Beattie, Phys. Rev., **36,** 132–145 (1930); *Temperature,* pp. 74–88, Reinhold Publ. Corp., New York, 1941.

[2] J. A. Beattie, D. D. Jacobus, J. M. Gaines, Jr., M. Benedict, and B. E. Blaisdell, Proc. Am. Acad. Arts Sci., **74,** 327–342 (1941).

$$H = D_1 - D_2 + m\,(M_1 - M_2 - S_1 + S_2); \qquad (27)$$

and the heights h_1 and h_2 of the mercury menisci in the long and short arms of the manometer, respectively, are:

$$h_1 = m\,(M_1 - N_1), \qquad (28)$$

$$h_2 = m\,(M_2 - N_2), \qquad (29)$$

where:

$M_1[M_2]$ = average reading of micrometer head of upper [lower] telescope when the cross-hair of the ocular is set on the crown of the mercury meniscus in the long [short] arm of the manometer.

$N_1[N_2]$ = average reading on bottom of meniscus.

$S_1[S_2]$ = average reading on scale division $D_1[D_2]$.

$D_1[D_2]$ = scale division nearest cross-hair of upper [lower] telescope when set on $M_1[M_2]$.

m = number of units on the scale per one complete turn of the micrometer head; it is the same for both telescopes.

The scale corrections to be applied to the height H are: (1) the ruling error of the scale, (2) the thermal extension of the scale, and (3) the extension of the scale under its weight. The following relation is without appreciable error for a scale hung from its upper end:

$$p'' = H + \varepsilon_1 - \varepsilon_2 + \alpha_s H(t_s - t_{sn}) + \frac{\rho_s g_l}{2E_s} H(H + 2D_2)\,, \qquad (30)$$

where:

p'' = pressure (mm.) corrected for scale corrections.

ε_1 = scale correction (mm.) for the position $H + D_2$.

ε_2 = scale correction (mm.) for the position D_2.

α_s = mean coefficient of linear thermal expansion (°C.$^{-1}$) of the scale material from t_{sn} to t_s.

t_s = mean temperature (°C.) of the scale.

t_{sn} = temperature (°C.) at which scale was calibrated.

ρ_s = density (gm./mm.^{3}) of the scale material.

g_l = gravity (cm./sec.^{2}) at the laboratory.

E_s = Young's modulus (dynes/mm.^{2}) of the scale material.

Any other consistent set of units may be used in Eq. (30). The mercury corrections to be applied to p'' are: (1) the difference between the capillary depression of mercury in the long arm and in the short arm of the manometer, (2) the thermal dilation and the compressibility of mercury, and (3) the effect of gravity. The relation is:

$$p' = (p'' + \delta_1 - \delta_2)\,\frac{V(0,\,1)\,g_l}{V(t,\,p)\,g_n}\,, \qquad (31)$$

$$V(t,\,p) = V(0,\,1)\left[1 + \alpha_{Hg}\,t_{Hg}\right]\left[1 - \beta_{Hg}\,\frac{p' - 760}{2 \times 760}\right], \qquad (32)$$

where:

p' = corrected pressure (mm.) at crown of mercury meniscus in the short arm of the manometer.

δ_1 = capillary depression (mm.) of mercury in long arm of manometer.

δ_2 = capillary depression in short arm.

g_n = standard gravity, 980.665 cm./sec.^{2}

$V(0,\,1)$ = mean specific volume of mercury in a column 760 mm. high at 0° C.

$V(t, p)$ = mean specific volume of mercury in a column p' mm. high at a mean temperature of t_{Hg}.

t_{Hg} = mean temperature (°C.) of mercury column.

α_{Hg} = mean coefficient of thermal dilation (°C.$^{-1}$) of mercury from 0° to t_{Hg} °C.

β_{Hg} = mean coefficient of cubical compressibility (atm.$^{-1}$) of mercury from 0 to 3 atm. at mean room temperature.

Let

$$F = \frac{g_l}{g_n} \frac{1}{1 + \alpha_{Hg}\, t_{Hg}}; \tag{33}$$

then Eq. (31) may be written without appreciable error:

$$p' = \left[p'' + \delta_1 - \delta_2\right]\left[1 + \beta_{Hg} \frac{HF - 760}{1520}\right] F. \tag{34}$$

Substitution of the value of p'' from Eq. (30) and simplification gives without appreciable error:

$$p' = [H + \delta_1 - \delta_2 + \delta_3]\, F, \tag{35}$$

$$\delta_3 = \varepsilon_1 - \varepsilon_2 + \alpha_s\, H(t_s - t_{sn}) + \frac{\rho_s g_l}{2E_s} H(H + 2D_2) + \beta_{Hg}\, H \frac{HF - 760}{1520}. \tag{36}$$

In Eq. (36) the value of F for the mean room temperature may be used without appreciable error. This approximation together with the others made in deriving the above expressions introduces for a height H of 2000 mm. an error less than 1×10^{-4} mm. for a scale of invar, brass, or glass correct at 0° or 20° C. when used from a room temperature of 10° to 30° C.

For an invar scale, for which $t_{sn} = 20°$ C., $\alpha_s = 1.5 \times 10^{-6\circ}$ C.$^{-1}$, $\rho_s = 8.0 \times 10^{-3}$ grams/mm.^{3}, $g_l = 980.400$ cm./sec.^{2}, $E_s = 1.45 \times 10^{10}$ dynes/mm.^{2}, used to measure the height of a mercury column in millimeters at a mean room temperature of 27° C., at which $\beta_{Hg} = 4.0 \times 10^{-6}$ atm.$^{-1}$ and $F = 0.995$, we obtain:

$$\delta_3 = \varepsilon_1 - \varepsilon_2 + 1.5 \times 10^{-6}\, H\,(t_s - 20) + 2.89 \times 10^{-9}\, H\,(H - 692 + 0.19\, D_2). \tag{37}$$

For a manometer used in gas thermometric measurements D_2 is constant. Thus ε_2 and the diameter of the short arm at D_2 are constant; and ε_1 and the diameter of the long arm at $H + D_2$ are functions of H. For the use of Eq. (35) we may tabulate F as a function of t_{Hg}, δ_1 as a function of h_1 and H, δ_2 as a function of h_2, and δ_3 as a function of t_s and H.

3. Calculation of the Errors of Approximations

In the derivation of the equations in the succeeding sections higher order terms in certain expressions have been dropped. The value of each such term has been computed for the following cases:

Case I. A nitrogen gas thermometer with a bulb of Jena 16$^{\text{III}}$ glass or of vitreous silica loaded to a pressure of 1000 mm. at 0° C. and used from 0° to 450° C. The ratio of the dead space to the total volume is taken to be 0.005 with 5% of the dead space in the region of large thermal gradient, 20% in the connecting capillaries at room temperature, and 75% in the short arm of the manometer. The vertical height of the part of the system at the temperature of the bulb is taken to be 250 mm., that part in the region of large thermal gradient 500 mm., and that part at room temperature − 500 mm.

Case II. A helium gas thermometer with a bulb of Jena 16$^{\text{III}}$ or of Jena 1565$^{\text{III}}$ glass loaded to a pressure of 1000 mm. at 0° C., and used from 100° to − 200° C.; and one loaded to a pressure of 1000 mm. at − 183° C. and used from − 183° to − 260° C. The dead spaces and heights are taken to be the same as in Case I.

4. Correction of the Observed Pressure of a Constant Volume Gas Thermometer for the Non-Ideality of the Apparatus

The object of this section is to derive an equation for correction of the observed pressure p' at the mercury surface in the short arm of the manometer to the pressure p at the center of the bulb which would have been found if: (1) the gravitational field were absent; (2) the volume of the system were constant; and (3) all of the gas were at the temperature of the bulb.

A sketch of a constant volume gas thermometer is given in Fig. 1. AS is the main thermometer system, A_aS_a the auxiliary thermometer system.

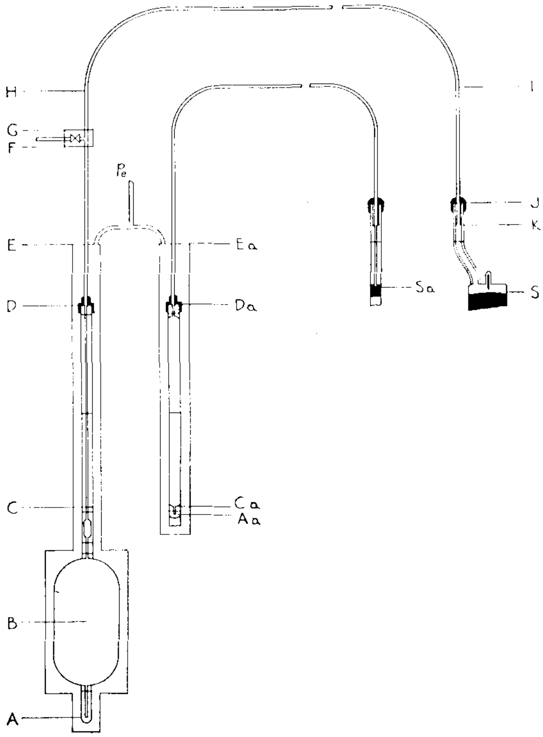

FIG. 1. Main gas thermometer system AS and auxiliary gas thermometer system A_aS_a.

(a) *Notation and Units*

In the use of the relations derived in this and the following sections any consistent set of units may be used. A suggested set is:

pressure in standard mm. of mercury,
volume in ml.,
area in ml./mm.,
length in mm.,
mass in moles for gases and grams for condensed systems,
temperature (T) in degrees Kelvin,
temperature (t) in degrees Centigrade on the International Scale,
the gas constant R = 62360 ml.-mm./°K.-mole.

The following symbols are used:

General. p = pressure.
V = volume.
T = Kelvin temperature.
t = Centigrade temperature on the International Scale.
N = number of moles of gas.
M = molecular weight of the gas.
A, B, C = parameters, functions of temperature, in the equation of state of a gas:

$$p\frac{V}{N} = A + Bp + Cp^2, \tag{38}$$

$$A \equiv RT. \tag{39}$$

δ_{Hg} = standard density of mercury (13.5955 gm./ml.).

Practical Gas Thermometer. x = distance along the axis of the thermometric system measured from A, the bottom of the bulb.

$a = a(x)$ = area of the section of the system at x normal to the axis.
$\pi = \pi(x)$ = pressure of the gas at x.
p' = pressure at the crown of the mercury meniscus in the short arm of the manometer.
$\phi = \phi(x)$ = hydrostatic head function at x defined by the relation $\pi = p'(1 + \phi)$.
p_e = pressure in the case surrounding the thermometer bulb.
$\delta_g = \delta_g(x)$ = density (moles/ml.) of the gas at x.
$T = T(x)$ = Kelvin temperature at x.
$\theta = \theta(x)$ = angle between an arrow in the axis of the thermometer pointing in the direction of increasing x and one pointing vertically upward.
l = vertical height, the algebraic sign being the same as that of $\cos\theta$. l_b is the vertical distance from the *center of the thermometer bulb* to the beginning of the dead space.
h_2 = height of mercury meniscus in the short arm of the manometer.
h_3 = distance from crown of meniscus to index mark in short arm of manometer.
a_m = area of short arm of manometer at the index mark.

Subscript a denotes that the quantity applies to the auxiliary gas thermometer.

Subscript b denotes the bulb.

Subscript d denotes the dead space taken as a whole.

Subscript i denotes the i-th dead space: $i = 1$ is the region of large thermal gradient contiguous to the bulb, $i = 2, 3, 4, \ldots$ are the successive contiguous dead space regions, $i = m$ is the dead space in the short arm of the manometer.

Subscript n denotes the value of a quantity at the standard condition of calibration. We took:

V_{bn} = volume of bulb at 0° C. and 1 atm. pressure inside and outside.

V_{in} = volume of i-th dead space ($i = 1, 2, \ldots m - 1$) at 27° C. and 1 atm. pressure.

V_{mn} = dead space volume in short arm of manometer above a horizontal plane through the index mark at 27° C. and 1 atm. pressure increased by a quantity Δ, which is somewhat less than the smallest expected volume below the plane through the index mark.

V_{ban} = volume of bulb of auxiliary thermometer at 27° C. and 1 atm. pressure.

V_{dan} = volume of total dead space of auxiliary thermometer at 27° C. and 1 atm. pressure.

Subscript r denotes the nominal (integral) International temperature of the thermostat for a run. Thus if $t_b = 150.0018°$, $t_r = 150°$ C.

Idealized Gas Thermometer. p = pressure. It is equal to p' plus the corrections for the deviation of the practical from the idealized instrument.

V = volume. It is equal to the volume of the practical instrument under the standard conditions of calibration, i. e., $V_{bn} + \sum_{1}^{m}{}_i V_{in}$.

Properties of Materials. α_b = mean coefficient of thermal dilation $(1/V_{bn})(\Delta V_b/\Delta t)°$ C.$^{-1}$, of the material of the bulb from $t_{bn}°$ to $t_r°$ C. at 1 atmosphere pressure; it is a function of temperature.

α_b' = true coefficient of thermal dilation $(1/V_{bn})(dV_b/dt)°$ C.$^{-1}$, of the material of the bulb at $t_r°$ C. and 1 atmosphere pressure; it is a function of temperature.

$\frac{\beta_b}{760}$ = mean coefficient of cubical compressibility, $-(1/V_{bn})(\Delta V_b/\Delta p)$ mm.$^{-1}$, of the material of the bulb from 0 to 3 atm. at $t_r°$ C.; it is a function of temperature.

γ_b = mean dilation, $\Delta V_b/(p_b - p_e)$ ml./mm., of the bulb at t_r° C. produced by difference between internal and external pressure; it is a function of temperature.

α_i = mean coefficient of thermal dilation (°C.$^{-1}$) of the material surrounding the i-th dead space ($i = 2, 3, 4, \ldots m$) from t_{in}° to t_i° C.

V_0 = covolume of mercury meniscus, i. e., gas volume below a horizontal plane through the crown of the meniscus.

(*b*) *General Relation*

The number of moles of gas in the practical gas thermometer, constant throughout all runs of the same ice-point pressure, is

$$N = \int_A^S \frac{\pi a dx}{A + B\pi + C\pi^2}, \tag{40}$$

$$= p' \int_A^S \frac{a(1+\phi)\,dx}{A + B(1+\phi)\,p' + C(1+\phi)^2\,p'^2} \equiv p' \int_A^S \psi dx. \tag{41}$$

In an equivalent idealized gas thermometer at the temperature T_b

$$N = \frac{pV}{A_b + B_b p + C_b\, p^2}. \tag{42}$$

Equating these two expressions for N and solving for the corrected pressure p, we obtain:

$$p = \frac{A_b p'}{V}\left\{1 + \frac{B_b p'}{V}\int_A^S \psi dx + \frac{C_b p p'}{V}\int_A^S \psi dx + \left[\frac{B_b{}^2 p'^2}{V^2} + \frac{2B_b C_b p p'^2}{V^2}\right]\left(\int_A^S \psi dx\right)^2 \right.$$
$$\left. + \frac{B_b{}^3 p'^3}{V^3}\left(\int_A^S \psi dx\right)^3 + \ldots\right\}\int_A^S \psi dx. \tag{43}$$

The expansion of ψ is

$$\psi = \frac{a}{A}\left\{1 - \frac{B}{A}p' + \phi - \frac{C}{A}p'^2 + \frac{B^2}{A^2}p'^2 - \frac{2B\phi}{A}p' + \frac{2BC}{A^2}p'^3 - \frac{B^3}{A^3}p'^3 + \ldots\right\}. \tag{44}$$

Substitution of this value of ψ into Eq. (43) and simplification gives

$$p = \frac{A_b p'}{V}\left\{\int_A^S \frac{a}{A}dx + \frac{B_b p'}{V}\left(\int_A^S \frac{a}{A}dx\right)^2 - p'\int_A^S \frac{Ba}{A^2}dx + \int_A^S \frac{\phi a}{A}dx\right\} + \frac{A_b p'}{V}\left\{\left[\frac{C_b p p'}{V}\left(\int_A^S \frac{a}{A}dx\right)^2\right.\right.$$
$$\left.\left. - p'^2\int_A^S \frac{Ca}{A^2}\,dx\right] + \left[p'^2\int_A^S \frac{B^2 a}{A^3}dx + \frac{B_b{}^2 p'^2}{V^2}\left(\int_A^S \frac{a}{A}\,dx\right)^3 - \frac{2B_b p'^2}{V}\int_A^S \frac{Ba}{A^2}\,dx \int_A^S \frac{a}{A}\,dx\right]\right\} + \ldots \tag{45}$$

The expression enclosed in the second set of braces consists of two groups of paired terms of opposite sign, each group enclosed in a bracket. These terms cancel almost completely for the bulb (A to C of Fig. 1) of the thermometer which contains practically all of the gas, and partly cancel for the gas in the dead space. If we drop these terms, substract p' from each side of the equation, add and subtract $\frac{p'}{V}\int_A^S a dx$ to the right hand side of the equation, replace A by RT, and correct p to an integral bulb temperature, we obtain

$$p - p' = \delta_4 + \delta_5 + \delta_6 + \delta_7 + \delta_8, \tag{46}$$

where:

$$\delta_4 = \frac{p'T_b}{V}\int_A^S \frac{\phi a}{T}\,dx = \text{gravitational correction.} \tag{47}$$

$\delta_5 = \frac{p'}{V}\left[\int_A^S a\,dx - V\right]$ = correction for variation of volume of the system on the assumption that the gas is ideal. (48)

$\delta_6 = \frac{p'}{V}\left[T_b\int_A^S \frac{a}{T}\,dx - \int_A^S a\,dx\right]$ = correction for variation of temperature of the system on the assumption that the gas is ideal. (49)

$$\delta_7 = \frac{p'^2 T_b}{RV}\left[\frac{B_b}{V}\left(\int_A^S \frac{a}{T}\,dx\right)^2 - \int_A^S \frac{Ba}{T^2}\,dx\right] = \text{correction to } (\delta_5 + \delta_6) \text{ for the imperfection of the gas.} \tag{50}$$

$$\delta_8 = p_0\,\alpha_v\,(t_r - t_b) = \text{correction to an integral temperature, } t_r. \tag{51}$$

The maximum error of Eq. (45) for either Case is 0.1 × 10^{-4} mm. of mercury; the maximum error of Eq. (46) is − 6 × 10^{-4} mm. for Case I (at 444.6° C.) and less than − 1 × 10^{-4} mm. for Case II (at − 260° C.).

(c) *Gravitational Correction*

The correction for the effect of the gravitational field is

$$\delta_4 = \frac{p'T_b}{V}\int_A^S \frac{\phi a}{T}\,dx. \tag{52}$$

Now

$$\int_\pi^{p'} d\pi = -\int_x^S \frac{M\delta_g}{\delta_{Hg}}\cos\theta\,dx. \tag{53}$$

Integration yields

$$\pi = p'\,(1 + \phi), \tag{54}$$

where

$$\phi = \frac{M}{\delta_{Hg}}\int_x^S \frac{\pi}{p'}\,\frac{\cos\theta\,dx}{A + B\pi + C\pi^2}. \tag{55}$$

Let:

$$\frac{\pi}{p'} = 1, \tag{56}$$

$$B = C = 0, \tag{57}$$

in the integrand of Eq. (55). Then

$$\phi = \frac{M}{R\delta_{Hg}}\int_x^S \frac{\cos\theta}{T}\,dx. \tag{58}$$

The assumptions (56) and (57) are justified since the maximum value of ϕ is 100 × 10^{-6} and its value is much smaller than this for the bulb which contains practically all of the gas.

Substitution of the value of ϕ from Eq. (58) into Eq. (52) gives:

$$\delta_4 = \frac{p'T_b}{V}\int_A^S \left(\frac{M}{R\delta_{Hg}}\int_x^S \frac{\cos\theta}{T}\,dx\right)\frac{a}{T}\,dx, \tag{59}$$

$$= 1.1795 \times 10^{-6} M \frac{p' T_b}{V} \int_A^S \left(\int_x^S \frac{\cos \theta}{T} \, dx \right) \frac{a}{T} \, dx, \tag{60}$$

$$= 1.1795 \times 10^{-6} M p' \left\{ \frac{V_b}{V} \left[\frac{l_b}{T_b} + \int_C^D \frac{\cos \theta}{T} \, dx + \sum_2^m {}_i \frac{l_i}{T_i} \right] + \frac{T_b}{V} \int_C^D \left(\int_x^S \frac{\cos \theta}{T} \, dx \right) \frac{a}{T} \, dx \right.$$
$$\left. + \sum_2^m {}_i \left[\frac{V_i}{V} \frac{T_b}{T_i} \left(\frac{l_i}{2T_i} + \sum_{i+1}^m {}_j \frac{l_j}{T_j} \right) \right] \right\}; \tag{61}$$

where CD is the region of large thermal gradient (see Fig. 1). Since the volume of the bulb is large compared to the volume of the dead space, Eq. (61) may be written:

$$\delta_4 = 1.1795 \times 10^{-6} M \frac{p' V_b}{V} \left[\frac{l_b}{T_b} + \int_C^D \frac{\cos \theta}{T} \, dx + \sum_2^m {}_i \frac{l_i}{T_i} \right]. \tag{62}$$

In a later section it will be shown that

$$\int_C^D \frac{\cos \theta}{T} \, dx = \frac{l_1}{T_1}, \tag{63}$$

where $1/T_1$ is evaluated by the use of the auxiliary thermometer $A_a S_a$. Thus:

$$\delta_4 = 1.1795 \times 10^{-6} M \frac{p' V_b}{V} \left[\frac{l_b}{T_b} + \sum_1^m {}_i \frac{l_i}{T_i} \right]. \tag{64}$$

The lengths l_b and l_i depend on temperature and the method of suspension of the thermometer bulb, and l_m depends on h_3.

The three approximations made are: (1) $\pi/p' = 1$, $B = C = 0$ in the evaluation of ϕ; (2) the dropping of certain terms of Eq. (61); and (3) the evaluation of δ_4 for the region CD by Eq. (63). The first two introduce a maximum error of -4×10^{-4} mm. of mercury for Case I and less than $+1 \times 10^{-4}$ mm. for Case II. The error introduced by the third assumption depends on the design of the apparatus. For our gas thermometers the error was $+3 \times 10^{-4}$ mm. of mercury when the bulb was at 444.6° C. and $+1 \times 10^{-4}$ mm. when at 180° C. for the run at 600 mm. ice-point loading.

(*d*) *Correction for Volume and Temperature Variations*

The correction for the variation of the volume of the system with temperature and pressure, and that for the variation of temperature are:

$$\delta_5 = \frac{p'}{V} \left[\int_A^S a dx - V \right], \tag{65}$$

$$\delta_6 = \frac{p'}{V} \left[T_b \int_A^S \frac{a}{T} \, dx - \int_A^S a dx \right]. \tag{66}$$

Integration yields:

$$\delta_5 = \frac{p'}{V} \left[\left(V_b - V_{bn} \right) + \left(\int_C^D a dx - V_{1n} \right) + \sum_2^m {}_i \left(V_i - V_{in} \right) \right], \tag{67}$$

$$\delta_6 = \frac{p'}{V} \left[\left(T_b \int_C^D \frac{a}{T} \, dx - \int_C^D a dx \right) + \sum_2^m {}_i V_i \left(\frac{T_b}{T_i} - 1 \right) \right]. \tag{68}$$

For the region of large thermal gradient CD the sum:

$$\left(\delta_5 + \delta_6\right)_{CD} = \frac{p'}{V}\left(T_b \int_C^D \frac{a}{T}\,dx - V_{1n}\right), \tag{69}$$

$$= \frac{p'}{V}\,V_{1n}\left(\frac{T_b}{T_1} - 1\right), \tag{70}$$

where V_{1n} is the volume of the region of large thermal gradient *at standard conditions* and $1/T_1$ is evaluated by use of the auxiliary thermometer. The derivation of Eq. (70) is given in a later section. Thus:

$$\delta_5 = \frac{p'}{V}\left[(V_b - V_{bn}) + \sum_2^m{}_i\,(V_i - V_{in})\right], \tag{71}$$

$$\delta_6 = \frac{p'}{V}\left[V_{1n}\left(\frac{T_b}{T_1} - 1\right) + \sum_2^m{}_i\,V_i\left(\frac{T_b}{T_i} - 1\right)\right]. \tag{72}$$

We may write with negligible error:

$$V_b - V_{bn} = V_{bn}\left[\alpha_b\,(t_r - t_{bn}) + \alpha_b'\,(t_b - t_r) - \frac{\beta_b}{760}\,(p' - 760)\right] + \gamma_b\,(p' - p_e), \tag{73}$$

$$V_i - V_{in} = V_{in}\,\alpha_i\,(t_i - t_{in}), \qquad (i = 2, 3, 4, \ldots m - 1) \tag{74}$$

$$V_m - V_{mn} = V_{mn}\,\alpha_m\,(t_m - t_{mn}) + \Delta V_m, \tag{75}$$

$$\Delta V_m = a_m\,h_3 + V_c - \Delta. \tag{76}$$

The quantity ΔV_m is the increase in the volume below a plane through the index mark in the short arm of the manometer from the value Δ. For manometer tubes 20 mm. in diameter we took Δ to be 0.1 ml. Then $(a_m\,h_3 + V_c)$ is always larger than Δ so that ΔV_m is always positive; and the value of δ_5 is much less than if we had considered ΔV_m to be the total quantity $(a_m\,h_3 + V_c)$.

The assumption that V_i is independent of pressure introduces a negligible error. The only other approximation made is the evaluation of $(\delta_5 + \delta_6)$ for the region CD by Eq. (70). The error introduced depends on the design of the apparatus. For our gas thermometers the error was $+ 25 \times 10^{-4}$ mm. of mercury when the bulb was at 444.6° C. and $+ 3 \times 10^{-4}$ mm. when at 180° C. for the run at 600 mm. ice-point loading.

(*e*) *Correction to δ_5 and δ_6 for the Departure of the Gas from a Perfect Gas*

The correction δ_7:

$$\delta_7 = \frac{p'^2 T_b}{RV}\left[\frac{B_b}{V}\left(\int_A^S \frac{a}{T}\,dx\right)^2 - \int_A^S \frac{Ba}{T^2}\,dx\right] \tag{77}$$

gives on integration

$$\delta_7 = \frac{p'^2 T_b}{RV}\left[\frac{B_b}{V}\left(\frac{V_b}{T_b} + \int_C^D \frac{a}{T}\,dx + \sum_2^m{}_i\,\frac{V_i}{T_i}\right)^2 - \left(\frac{V_b B_b}{T_b^2} + \int_C^D \frac{Ba}{T^2}\,dx + \sum_2^m{}_i\,\frac{V_i B_i}{T_i^2}\right)\right]. \tag{78}$$

The first integral of Eq. (78) can be evaluated as

$$\int_C^D \frac{a}{T}\,dx = \frac{V_{1n}}{T_1}, \tag{79}$$

and the second approximated as

$$\int_C^D \frac{Ba}{T^2}\,dx = \frac{B_1}{T_1}\int_C^D \frac{a}{T}\,dx = \frac{B_1 V_{1n}}{T_1^2}, \tag{80}$$

by use of the indications of the auxiliary thermometer, where B_1 is the value of the second virial coefficient of the gas at T_1.

Carrying out the indicated operations and dropping the squares and products of small terms, we obtain from Eq. (78):

$$\delta_7 = \frac{p'^2}{RV}\left[\frac{B_b V_b}{V}\left(\frac{V_b - V}{T_b} + 2\sum_1^m{}_i \frac{V_i}{T_i}\right) - T_b \sum_1^m{}_i \frac{B_i V_i}{T_i^2}\right], \tag{81}$$

where V_i signifies V_{1n} for $i = 1$. If we put the ratio $V_b/V = 1$ the error is of opposite sign and of the same order as that made in the terms dropped in Eq. (78) when either error is at all appreciable; also T_r can be written for T_b with no perceptible error.

Hence Eq. (81) may be written:

$$\delta_7 = \frac{p'^2}{RV}\left[B_r\left(\frac{V_b - V}{T_r} + 2\sum_1^m{}_i \frac{V_i}{T_i}\right) - T_r \sum_1^m{}_i \frac{B_i\ V_i}{T_i^2}\right], \tag{82}$$

where B_r is the value of B at T_r.

The approximations made are: (1) the dropping of certain terms of Eq. (78) and placing $V_b/V = 1$ in Eq. (81); and (2) the evaluation of δ_7 for the region CD by Eqs. (79) and (80). The maximum error of the first is $+ 2 \times 10^{-4}$ mm. of mercury for Case I and less than $- 1 \times 10^{-4}$ mm. for Case II. The error introduced by the second depends on the design of the apparatus. For our gas thermometers the error was $+ 1 \times 10^{-4}$ mm. of mercury when the bulb was at 444.6° C. and 0×10^{-4} mm. when at 180° C. for the 600 mm. ice-point loading.

(*f*) *Correction to an Integral Temperature*

The temperature t_b of the thermostat surrounding the bulb will in general differ from the nominal (integral) temperature t_r of the run by several thousandths of a degree. The correction for this effect is

$$\delta_8 = p_0\, \alpha_v\, (t_r - t_b), \tag{83}$$

where p_0 is the ice-point pressure for the run and α_v is the approximate mean coefficient of thermal pressure increase at constant volume from 0° to 100° C. of the gas for an ice-point pressure p_0.

(*g*) *Summary of Errors Introduced by the Approximations*

The maximum errors of all approximations made in deriving the preceding equations are $- 8 \times 10^{-4}$ mm. of mercury for Case I and $- 1 \times 10^{-4}$ mm. for Case II. In addition there is the error of the evaluation of the corrections for the region CD of large thermal gradient by use of the indications of the auxiliary thermometer. We determined this error experimentally for our gas thermometer and found it to be $+ 29 \times 10^{-4}$ mm. for a bulb temperature of 444.6° C. and $+ 4 \times 10^{-4}$ mm. for a bulb temperature of 180° C. for the run with an ice-point pressure of 600 mm. The error is almost proportional to the ice-point pressure for any one temperature. It will be noticed that this error decreases rapidly with decreasing temperature difference from room temperature.

(*h*) *Other Sources of Error*

Other sources of error that should be considered in the design and operation of a gas thermometer are:

(1) Calibration errors.
(2) Errors in the assumed properties of materials, especially in the coefficient of thermal expansion of the material of the bulb.
(3) Hysteresis in the properties of materials, especially in the effect of pressure and temperature on the volume of the bulb.
(4) Ageing effects, especially the effect of time on the length of the scale.
(5) Passage of gas through the walls of the thermometer system.
(6) Adsorption of gas on the walls of the thermometer bulb.
(7) Thermal diffusion pressure.

The design of a constant volume thermometer with a view to eliminating the effects of these sources of error to a greater or less extent and the methods of testing the achievement of this result are given in the preceding paper.[2]

The thermal diffusion pressure can be estimated from an equation[3] which has been tested for helium from room temperature to liquid helium temperatures. For nitrogen in a tube of 0.70 mm. bore, one temperature being 450° and the other 27° C., the computed effect is 5×10^{-4} mm. of mercury for a pressure of 871 mm. ($p_0 = 333$ mm.), and 2.5×10^{-4} mm. for a pressure of 1569 mm. ($p_0 = 600$ mm.).

5. Theory and Performance of the Auxiliary Thermometer

(a) *Theory*

In the preceding section there occurred three expressions:

$$\delta_{4CD} = 1.1795 \times 10^{-6} M \frac{p' V_b}{V} \int_C^D \frac{\cos\theta}{T}\, dx, \tag{84}$$

$$\left(\delta_5 + \delta_6\right)_{CD} = \frac{p'}{V}\left(T_b \int_C^D \frac{a}{T}\, dx - V_{1n}\right), \tag{85}$$

$$\delta_{7CD} = \frac{p'^2}{RV}\left(2B_r \int_C^D \frac{a}{T}\, dx - T_r \int_C^D \frac{Ba}{T^2}\, dx\right), \tag{86}$$

for the region of large thermal gradient *CD*, Fig. 1. This gradient may be quite large so that the device of segregation of *CD* into several regions essentially isothermal and evaluation of the integrals as sums of terms would require many terms and thus a prohibitive amount of labor. The three integrals:

$$\int_C^D \frac{a}{T}\, dx, \qquad \int_C^D \frac{\cos\theta}{T}\, dx, \qquad \int_C^D \frac{Ba}{T^2}\, dx,$$

can be evaluated, the first two quite exactly, and the last approximately, by use of the auxiliary gas thermometer A_aS_a, Fig. 1.

For the nitrogen thermometer of Case I at 450° C., $\delta_{4CD} = 0.1$ mm., $(\delta_5 + \delta_6)_{CD} = 0.4$ mm., and $\delta_{7CD} = 0.003 - 0.0015 = 0.0015$ mm.

A theory of the auxiliary thermometer has been outlined by Henning.[4]

The relations derived in the preceding sections may be applied to the auxiliary thermometer. Some further approximations can be made without the introduction of serious error. In the computation of p_a' from Eq. (35) we may write:

$$\delta_{1a} - \delta_{2a} = \delta_a, \tag{87}$$

$$\delta_{3a} = 0, \tag{88}$$

where δ_a is the mean capillary depression correction (a constant value) applied to all observations. Thus

$$p_a' = (H_a + \delta_a)\, F_a. \tag{89}$$

In the application of Eq. (41) to the auxiliary thermometer we may write

$$B_a = C_a = \phi_a = 0; \tag{90}$$

whence:

$$N_a = p_a' \int_{A_a}^{S_a} \frac{a_a}{A_a}\, dx_a, \tag{91}$$

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[3] S. Weber, W. H. Keesom, and G. Schmidt, Kamerlingh Onnes Lab., Univ. of Leiden, Comm. No. **246a,** 1–16.

[4] F. Henning, *Temperaturmessung,* p. 46, F. Vieweg und Sohn, Braunschweig, 1915.

$$= \frac{p_a'}{R} \int_{A_a}^{S_a} \frac{a_a}{T_a}\, dx_a. \tag{92}$$

Let:

$$\int_{A_a}^{D_a} a_a dx_a = V_{ba}, \tag{93}$$

$$\int_{D_a}^{S_a} a_a dx_a = \sum_{1}^{m}{}_i V_{ia} = V_{da}, \tag{94}$$

$$r_{an} = \frac{V_{dan}}{V_{ban} + V_{dan}} \equiv \frac{V_{dan}}{V_{an}}. \tag{95}$$

The volume of the bulb is assumed to depend only on temperature; and that of the dead space is assumed to be constant. The coefficient of thermal expansion of the material of the bulb is the same as that of the capillary *CD* of the main thermometer.

In order to calibrate the auxiliary thermometer for the evaluation of the integrals of Eqs. (84) to (86), the bulb is thermostated at the standard temperature T_{ban}, and the pressure p'_{an} and mean temperature T_{dan} of the dead space determined. From Eq. (92):

$$\frac{N_aR}{V_{an}} = \frac{p'_{an}}{V_{an}}\left(\frac{V_{ban}}{T_{ban}} + \frac{V_{dan}}{T_{dan}}\right) = p'_{an}\left(\frac{1 - r_{an}}{T_{ban}} + \frac{r_{an}}{T_{dan}}\right) \equiv \Phi_{an}, \tag{96}$$

where Φ_{an} is a constant for all runs made with a given loading of the auxiliary thermometer.

When the auxiliary thermometer is used in a gas thermometer run, the pressure p_a' and the mean temperature T_{da} of the dead space are determined. Then

$$\frac{N_aR}{V_{an}} = \frac{p_a'}{V_{an}}\left(\int_{A_a}^{D_a} \frac{a_a}{T_a}\, dx_a + \frac{V_{dan}}{T_{da}}\right). \tag{97}$$

From Eq. (97) and the calibration data of Eq. (96), we obtain

$$\int_{A_a}^{D_a} \frac{a_a}{T_a}\, dx_a = \frac{\Phi_{an} V_{an}}{p_a'} - \frac{V_{dan}}{T_{da}}. \tag{98}$$

Let the capillary *CD* of the main thermometer and the bulb A_aD_a of the auxiliary thermometer fulfill the conditions that in every horizontal plane:

$$T(x) = T_a(x_a), \tag{99}$$

$$a(x) = k\, a_a(x_a), \tag{100}$$

where k is independent of x and of temperature. Then:

$$\frac{\displaystyle\int_C^D \frac{a}{T}\, dx}{\displaystyle\int_C^D a dx} = \frac{\displaystyle\int_{A_a}^{D_a} \frac{a_a}{T_a}\, dx_a}{\displaystyle\int_{A_a}^{D_a} a_a dx_a}, \tag{101}$$

or

$$\int_C^D \frac{a}{T}\, dx = \frac{V_1}{V_{ba}} \int_{A_a}^{D_a} \frac{a_a}{T_a}\, dx_a, \tag{102}$$

$$= \frac{V_{1n}}{V_{ban}} \int_{A_a}^{D_a} \frac{a_a}{T_a}\, dx_a, \tag{103}$$

since the coefficients of thermal dilation of CD and A_aD_a are the same. Substitution from Eq. (98) into Eq. (103) gives:

$$\int_C^D \frac{a}{T}\, dx = \left(\frac{\Phi_{an}V_{an}}{p_a'} - \frac{V_{dan}}{T_{da}}\right)\frac{V_{1n}}{V_{ban}}. \tag{104}$$

Let

$$\frac{1}{T_1} \equiv \frac{1}{V_{ban}}\left(\frac{\Phi_{an}V_{an}}{p_a'} - \frac{V_{dan}}{T_{da}}\right) = \frac{\dfrac{\Phi_{an}}{p_a'} - \dfrac{r_{an}}{T_{da}}}{1 - r_{an}}. \tag{105}$$

The quantity $1/T_1$ is the reciprocal temperature along A_aD_a, hence by hypothesis that along CD, averaged with respect to area. Then

$$\int_C^D \frac{a}{T}\, dx = \frac{V_{1n}}{T_1}. \tag{106}$$

If the bore of CD is uniform,

$$\int_C^D \frac{\cos\theta}{T}\, dx = \frac{l_1}{T_1}. \tag{107}$$

Finally let B/T be constant for the gas in CD and have its value B_1/T_1, at T_1. Then

$$\int_C^D \frac{Ba}{T^2}\, dx = \frac{B_1V_{1n}}{T_1^2}. \tag{108}$$

The integrals given at the beginning of the section can now be evaluated as:

$$\delta_{4CD} = 1.1795 \times 10^{-6}\, M\, \frac{p'V_b}{V}\, \frac{l_1}{T_1}, \tag{109}$$

$$\left(\delta_5 + \delta_6\right)_{CD} = \frac{p'}{V}\, V_{1n}\left(\frac{T_b}{T_1} - 1\right), \tag{110}$$

$$\delta_{7CD} = \frac{p'^2}{RV}\left(2B_r\,\frac{V_{1n}}{T_1} - T_r\,\frac{B_1V_{1n}}{T_1^2}\right). \tag{111}$$

(*b*) *Assumptions Made in the Derivation*

The assumptions made in the above derivation are:

(1) For the auxiliary manometer: $\delta_1 - \delta_2 = \delta_a$ (a constant) and $\delta_3 = 0$.
(2) For the gas in the auxiliary thermometer: $B_a = C_a = \phi_a = 0$.
(3) The volume of the bulb of the auxiliary thermometer depends only on temperature; the dead space volume is constant.
(4) For the capillary CD and the tube A_aD_a: $a\,(x) = ka_a\,(x_a)$ where k is independent of x (or x_a) and of temperature.
(5) For CD and A_aD_a: $T\,(x) = T_a\,(x_a)$ in each horizontal plane.
(6) For CD: the area a is constant and $\cos\theta = 1$.
(7) For the gas in CD: B/T is constant and has the value B_1/T_1.

Assumptions (1) to (3) affect the computed value of $1/T_1$. If we take maximum values[5] for the effects of these assumptions, the errors in T_1 are less than 0.6, 0.2, and 0.1° C. for thermostat temperatures of 444.6°, 100°, and 0° C., respectively, when the auxiliary thermometer is filled with nitrogen to a pressure of 1000 mm. at 0° C.; and the errors are less than 0.1° C. for all thermostat temperatures from 100° to − 260° C. for a thermometer filled with helium to 1000 mm. at 0° C. The error is proportional to the ice-point pressure of the thermometer.

(c) *Elimination of the Error Due to Assumption (4)*

The error introduced into Eqs. (109) to (111) by the assumption that k, Eq. (100), is independent of x can be eliminated for any one thermostat temperature if the areas and corresponding temperatures of CD and A_aD_a are known as functions of the respective coordinates x and x_a. At the same time the proper lengths of CD to be associated with the short capillary sections at the ends of A_aD_a are determined. Computation has shown that if the error is eliminated for the thermostat temperature farthest from room temperature it will also be eliminated for all other thermostat temperatures.

From a plot of the indications of thermocouples (placed along CD) against x, we can determine the temperature at the middle of each of the m one-centimeter intervals of CD, each assumed to be isothermal. The most important integral of Eqs. (84) to (86) to be evaluated in order to obtain Eqs. (109) to (111) could then be computed as the sum:

$$T_r \int_C^D \frac{a}{T}\,dx = T_r \sum_1^m {}_j \frac{V_j}{T_j} \tag{112}$$

where V_j and T_j are the volume and Kelvin temperature of the j-th one-centimeter interval of CD and T_r is the nominal temperature of the thermostat. If assumption (4) is fulfilled:

$$T_r \sum_1^m {}_j \frac{V_j}{T_j} = T_r \frac{V_{1n}}{V_{ban}} \sum_1^m {}_j \frac{V_{aj}}{T_{aj}} \tag{113}$$

where

$$T_j = T_{aj},\ V_{1n} = \sum_1^m {}_j\, V_{nj},\ V_{ban} = \sum_1^m {}_j\, V_{anj} \tag{114}$$

and V_{aj} is the volume of the j-th one-centimeter section of the bulb of the auxiliary thermometer. The assumptions made are: (1) $T_j = T_{aj}$, and (2) the coefficients of thermal dilation of V_j and V_{aj} are the same ($j = 1, 2, \ldots m$). By slight adjustment of the length of the top or bottom section of CD or both, we can cause Eq. (113) to be completely satisfied. This new length of CD is then taken as the value of l_1 at T_r from which l_{1n} can be computed.

We measured the temperature along CD of our two gas thermometers by means of seven thermocouples for a thermostat temperature of 444.6° C. and one of 180° C. The values of the lengths of the end sections of CD that satisfied Eq. (113) for 444.6° C. also satisfied it for 180° C.

The region below CD is assigned to the bulb of the main thermometer, the region above to the dead space 2.

(d) *Performance of the Auxiliary Thermometer*

With the elimination of the error due to assumption (4) we have left the error in the computed value of $1/T_1$ due to assumptions (1) to (3) and the errors due to assumptions (5) to (7). The size of these errors were determined for our gas thermometer by the determination of the value of δ_{4CD}, $(\delta_5 + \delta_6)_{CD}$, and δ_{7CD} from Eqs. (109), (110), and (111), where $1/T_1$ was evaluated from the auxiliary thermometer by Eq. (105); and from Eqs. (84), (85), and (86), the integrals being evaluated as sums of 45 terms, each for a one-centimeter section of CD. When t_r was 444.6 C. and the ice-point pressure in the main thermometer was 600 mm. the errors in δ_{4CD}, $(\delta_5 + \delta_6)_{CD}$, and δ_{7CD} were 3×10^{-4}, 25×10^{-4}, and 1×10^{-4} mm. of mercury, respectively, a total of 0.003 mm., which is within the probable accuracy of the thermocouple method. When t_r was 180° C., these errors were 1×10^{-4} mm., 3 ×

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[5] The computations were made for $V_{da}/V_{ba} = 0.1$, $A_aD_a = 500$ mm., error of assumption (1) = 0.1 mm. in p'_{an} and p_a', variation in $t_{da} = \pm 5°$ C., $p_a' = 2$ atm., $p_{ca} - p_a' = 1.5$ atm.

10^{-4} mm., and 0×10^{-4} mm., respectively, a total of about 0.0005 mm. The errors fall rapidly with decreasing temperature difference from room temperature.

6. CORRECTION OF THE OBSERVED VOLUME OF A CONSTANT PRESSURE GAS THERMOMETER FOR THE NON-IDEALITY OF THE APPARATUS

The method given in a previous section is directly applicable to the constant pressure gas thermometer. Two procedures are possible:

(1) The idealized thermometer is taken to be one in which all of the gas is at the bulb temperature. Eqs. (11) and (13) are to be used for computing α_p and t_p. The pipettes are treated as part of the dead space.

(2) The idealized thermometer is taken to be one with a bulb at the thermostat temperature and a pipette at some fixed temperature, say 0° C. Eqs. (17) and (18) are to be used for computing α_p and t_p. The pipettes are now not a part of the dead space.

Fig. 1 may serve as an illustration of a constant pressure gas thermometer if the pipette is imagined as being inserted between *H* and *I*. The bulb is *AC* and the rest of the system including the pipette is *CS*.

(*a*) *Method I*

Let V be the (variable) volume of the bulb at T_b. Application of Eqs. (41) and (42) gives:

$$\frac{p_0 V}{A_b + B_b p_0 + C_b p_0^2} = p' \int_A^S \frac{a\,(1+\phi)\,dx}{A + B\,(1+\phi)\,p' + C\,(1+\phi)^2\,p'^2}. \tag{115}$$

Solving for V and substituting from Eq. (44), we obtain:

$$V = \frac{A_b p'}{p_0}\left\{\int_A^S \frac{a}{A}\,dx + \frac{B_b p_0}{A_b}\int_A^S \frac{a}{A}\,dx - p'\int_A^S \frac{Ba}{A^2}\,dx + \int_A^S \frac{\phi a}{A}\,dx\right\} + \frac{A_b p'}{p_0}\left\{\left[\frac{C_b p_0^2}{A_b}\int_A^S \frac{a}{A}\,dx - p'^2\int_A^S \frac{Ca}{A^2}\,dx\right] + \left[p'^2\int_A^S \frac{B^2 a}{A^3}\,dx - \frac{B_b p_0 p'}{A_b}\int_A^S \frac{Ba}{A^2}\,dx\right]\right\} + \ldots . \tag{116}$$

The paired terms in the second brace are dropped. Let

$$V' = V_{bn} + \sum_{1}^{m}{}_{i}\, V_{in} + V_{Hg}, \tag{117}$$

where V_{Hg} is the volume of mercury run out of the pipette. Then

$$V - V' = \delta_4 + \delta_{5.1} + \delta_{5.2} + \delta_6 + \delta_7 + \delta_8, \tag{118}$$

where:

$$\delta_4 = \frac{p' T_b}{p_0}\int_A^S \frac{\phi a}{T}\,dx = \text{gravitational correction.} \tag{119}$$

$\delta_{5.1} = \dfrac{p'}{p_0}\left[\displaystyle\int_A^S a dx - V'\right]$ = correction for variation of volume of the system on the assumption that the gas is ideal. (120)

$\delta_{5.2} = \dfrac{p'}{p_0} V'\left(1 - \dfrac{p_0}{p'}\right)$ = correction for deviation of p' from p_0 on the assumption that the gas is ideal. (121)

$\delta_6 = \dfrac{p'}{p_0}\left[T_b\displaystyle\int_A^S \frac{a}{T}\,dx - \int_A^S a dx\right]$ = correction for variation in temperature of the system on the assumption that the gas is ideal. (122)

$\delta_7 = \frac{p'^2}{Rp_0}\left[\frac{B_b p_0}{p'}\int_A^S \frac{a}{T}\,dx - T_b\int_A^S \frac{Ba}{T^2}\,dx\right]$ = correction to $(\delta_{5.1} + \delta_{5.2} + \delta_6)$ for the imperfection of the gas. (123)

$\delta_8 = V_0\alpha_p\,(t_r - t_b)$ = correction to an integral temperature, t_r. The quantity V_0 is the ice-point volume of the run. (124)

The corrected volumes, V, are to be used in Eqs. (11) and (13) for computing α_p and t_p. The pressure p_0 is constant for all runs with the same ice-point pressure. It may be taken equal to p' for the run at 0° C.

(*b*) *Method II*

In the idealized thermometer let V_b be the (constant) volume (AC, Fig. 1) of the bulb at T_b and v the (variable) volume (CS, Fig. 1) of the pipette at T_0. Application of Eqs. (41) and (42) gives:

$$\frac{p_0V_b}{A_b + B_bp_0 + C_bp_0^2} + \frac{p_0v}{A_0 + B_0p_0 + C_0p_0^2} = p'\int_A^S \frac{a\,(1+\phi)\,dx}{A + B\,(1+\phi)p' + C\,(1+\phi)^2\,p'^2}. \tag{125}$$

Solving for v and substituting from Eq. (44), we obtain:

$$\begin{aligned} v = \frac{A_0p'}{p_0}&\left\{\int_A^S \frac{a}{A}\,dx - \frac{V_bp_0}{A_bp'} + \frac{B_0p_0}{A_0}\int_A^S \frac{a}{A}\,dx - p'\int_A^S \frac{Ba}{A^2}\,dx - \frac{V_bp_0^2}{A_bp'}\left(\frac{B_0}{A_0} - \frac{B_b}{A_b}\right) + \int_A^S \frac{\phi a}{A}\,dx\right\} \\ &+ \frac{A_0p'}{p_0}\left\{\left[\frac{C_0p_0^2}{A_0}\int_A^S \frac{a}{A}\,dx - p'^2\int_A^S \frac{Ca}{A^2}\,dx - \frac{V_bp_0^3}{A_bp'}\left(\frac{C_0}{A_0} - \frac{C_b}{A_b}\right)\right]\right. \\ &\left. + \left[p'^2\int_A^S \frac{B^2a}{A^3}\,dx - \frac{B_0p_0p'}{A_0}\int_A^S \frac{Ba}{A^2}\,dx - \frac{V_bp_0^3}{A_bp'}\,\frac{B_b}{A_b}\left(\frac{B_b}{A_b} - \frac{B_0}{A_0}\right)\right]\right\} + \ldots \end{aligned} \tag{126}$$

The paired terms in the second brace are dropped. Let

$$v' = \sum_1^m {}_i\, v_{in} + v_{Hg}, \tag{127}$$

where v_{Hg} is the volume of mercury run out of the pipette. Then

$$v - v' = \delta_4 + \delta_{5.1} + \delta_{5.2} + \delta_6 + \delta_7 + \delta_8, \tag{128}$$

where:

$$\delta_4 = \frac{p'\,T_0}{p_0}\int_A^S \frac{\phi a}{T}\,dx. \tag{129}$$

$$\delta_{5.1} = \frac{p'}{p_0}\left[\frac{T_0}{T_b}\left(\int_A^C a\,dx - V_b\right) + \left(\int_C^S a\,dx - v'\right)\right]. \tag{130}$$

$$\delta_{5.2} = \frac{p'}{p_0}\left(\frac{V_b\,T_0}{T_b} + v'\right)\left(1 - \frac{p_0}{p'}\right). \tag{131}$$

$$\delta_6 = \frac{p'}{p_0}\left[T_0\int_A^S \frac{a}{T}\,dx - \frac{T_0}{T_b}\int_A^C a\,dx - \int_C^S a\,dx\right]. \tag{132}$$

$$\delta_7 = \frac{p'^2}{Rp_0}\left[\frac{B_0\,p_0}{p'}\int_A^S \frac{a}{T}dx - T_0\int_A^S \frac{Ba}{T^2}\,dx - V_b\,\frac{T_0\,p_0^2}{T_b\,p'^2}\left(\frac{B_0}{T_0} - \frac{B_b}{T_b}\right)\right]. \tag{133}$$

$\delta_8 = \frac{V_b\alpha_pT_0^2}{T_b^2}\,(t_r - t_b)$. The quantity V_b is the volume of the bulb at standard conditions. (134)

The corrected volumes, v, are to be used in Eqs. (17) and (18) for the computation of α_p and t_p.

The further reduction of Eqs. (119) to (124) or Eq. (129) to (134) can be carried out in a manner similar to that used in a preceding section for the constant volume gas thermometer.

7. Correction of the Thermometric Coefficients and Gas Temperatures for the Imperfection of the Gas

When the pressures or volumes corrected for the deviations of the experimental thermometer from the corresponding idealized one are substituted into the proper one of the Eqs. (1) to (22), there result values of α_v, t_v, α_p, or t_p which depend upon the gas used and the ice-point pressure of the run. The computation of the corresponding values of these quantities for zero pressure, see Eqs. (23) to (25), is usually made from compressibility data on the gas employed or from measured Joule-Thomson and Joule coefficients supplemented if necessary by compressibility data.

There is a rather extensive literature on this subject.[6]

(a) *Correction from Compressibility Data*

The isothermal compressibility data for a constant mass of a gas can be fitted in the low pressure region by an equation of the type:

$$pV = A + Bp + Cp^2; \tag{135}$$

or one of the type:

$$pV = A\left(1 + \frac{B}{V} + \frac{C'}{V^2}\right), \tag{136}$$

where A, B, C, C' are functions only of temperature for a given gas. The quantities A and B should have the same numerical values in Eq. (136) as in Eq. (135), and

$$C' = AC + B^2; \qquad C = \frac{C' - B^2}{A}. \tag{137}$$

It can be shown [1] that A must obey the relations

$$\frac{A}{A_0} = \frac{T}{T_0} = 1 + \alpha t, \tag{138}$$

and if V is the volume of one mole of gas

$$A = RT, \tag{139}$$

where R is the universal gas constant, T is Kelvin temperature, t the corresponding absolute Centigrade temperature, T_0 the Kelvin temperature of the ice-point, and α the thermometric coefficient of an ideal gas.

When Eqs. (135) and (136) are applied to isothermal compressibility data, say by the method of least squares, the relations between B, C, and C' given above will not be satisfied exactly. Eq. (136) gives a better representation of the measurements than Eq. (135) when the same pressure range is considered.

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For the purposes of writing some of the following equations in more condensed form, let us define:

$$\Delta(x) \equiv \begin{vmatrix} 1 & 1 & 1 \\ x_0 T_0 & x_{100} T_{100} & x_t T \\ T_0 & T_{100} & T \end{vmatrix},$$

$$= (x_{100} T_{100} - x_0 T_0)\, t - (x_t T - x_0 T_0)\, 100, \tag{140}$$

$$= (x_{100} - x_0)\, T_{100} t - (x_t - x_0)\, 100 T, \tag{141}$$

where T is Kelvin temperature, $t = T - T_0$, and the subscripts 0 and 100 refer to 0° and 100° C. When the symbol $\Delta\,(x)_v$ [or $\Delta\,(x)_p$] is used, t is to be replaced by the gas temperature t_v, [or t_p], as defined in Eqs. (6) or (13); and T by $(T_0 + t_v)$, [or $(T_0 + t_p)$]. Thus:

$$\Delta(B) = (B_{100} - B_0)\, T_{100} t - (B_t - B_0)\, 100 T,$$

$$\Delta(B)_v = (B_{100} - B_0)\, T_{100} t_v - (B_t - B_0)\, 100\, (T_0 + t_v),$$

$$\Delta(B/T) = (B_{100} - B_0)\, t - (B_t - B_0)\, 100,$$

etc. The values of the virial coefficients B, C, C' at any temperature should be independent of the value assigned to the temperature. Actually, since A_t is computed as $A_0\, T/T_0$, the values of B, C, and C' do depend to some extent on the value assigned to T, which should be on the Kelvin scale.

Constant Volume Gas Thermometer. For the constant volume gas thermometer the mass of gas is constant and V is constant and has the value V_0. The following relations will be found useful in the treatment of the data:

$$pV_0 = A + B \frac{A}{A_0} p_0 + \left[C + \frac{B}{A} (B - B_0) \right] \frac{A^2}{A_0^2} p_0^2\,, \tag{142}$$

$$= A \left\{ 1 + B \frac{p_0}{A_0} + \left[C' - B\, B_0 \right] \frac{p_0^2}{A_0^2} \right\}, \tag{143}$$

$$\frac{p}{p_0} = \frac{A}{A_0} \left\{ 1 + (B - B_0) \frac{p_0}{A_0} + \left[(CA - C_0\, A_0) + (B - B_0)^2 \right] \frac{p_0^2}{A_0^2} \right\}, \tag{144}$$

$$= \frac{A}{A_0} \left\{ 1 + (B - B_0) \frac{p_0}{A_0} + \left[(C' - C_0') - 2B_0\, (B - B_0) \right] \frac{p_0^2}{A_0^2} \right\}, \tag{145}$$

$$\frac{p_0}{p} = \frac{A_0}{A} \left\{ 1 - (B - B_0) \frac{p_0}{A_0} - (CA - C_0\, A_0) \frac{p_0^2}{A_0^2} \right\}, \tag{146}$$

$$= \frac{A_0}{A} \left\{ 1 - (B - B_0) \frac{p_0}{A_0} - \left[(C' - C_0') - (B^2 - B_0^2) \right] \frac{p_0^2}{A_0^2} \right\}. \tag{147}$$

Substitution of the values of pV_0 from Eqs. (142) and (143) into Eq. (4) yields:

$$\alpha = \alpha_v - \frac{1 + 100\alpha}{100} \frac{B_{100} - B_0}{A_0} p_0 \left\{ 1 + \left[\frac{C_{100}\,(1 + 100\alpha) - C_0}{B_{100} - B_0} + \frac{B_{100} - B_0}{A_0} \right] p_0 \right\}, \tag{148}$$

$$= \alpha_v - \frac{1 + 100\alpha}{100} \frac{B_{100} - B_0}{A_0} p_0 \left\{ 1 + \left[\frac{C'_{100} - C_0'}{B_{100} - B_0} - 2B_0 \right] \frac{p_0}{A_0} \right\}. \tag{149}$$

Substitution of the values of pV_0 into Eq. (7) yields:

$$t = t_v + \frac{\Delta(B)}{100 A_0} p_0 \left\{ 1 + \left[\frac{100 A_0}{T_0} \frac{\Delta(CT)}{\Delta(B)} + 100 \frac{\Delta(B^2)}{\Delta(B)} - (B_{100} + B_0)\, T_{100} + 2B_0 T_0 \right] \frac{p_0}{100 A_0} \right\}. \tag{150}$$

$$= t_v + \frac{\Delta(B)}{100 A_0} p_0 \left\{ 1 + \left[100 \frac{\Delta(C')}{\Delta(B)} - (B_{100} + B_0)\, T_{100} + 2B_0 T_0 \right] \frac{p_0}{100 A_0} \right\}. \tag{151}$$

Eqs. (148) to (151) may be written:

$$\alpha = \alpha_v - \frac{1 + 100\alpha_v}{100}\,\frac{B_{100} - B_0}{A_0}\,p_0\left\{1 + \frac{C_{100}\,(1 + 100\alpha_v) - C_0}{B_{100} - B_0}\,p_0\right\}, \tag{148a}$$

$$= \alpha_v - \frac{1 + 100\alpha_v}{100}\,\frac{B_{100} - B_0}{A_0}\,p_0\left\{1 + \left[\frac{C'_{100} - C_0'}{B_{100} - B_0} - (B_{100} + B_0)\right]\frac{p_0}{A_0}\right\}, \tag{149a}$$

$$t = t_v + \frac{\Delta(B)_v}{100A_0}\,p_0\left\{1 + \left[\frac{A_0}{T_0}\,\frac{\Delta(CT)_v}{\Delta(B)_v} + \frac{\Delta(B^2)_v}{\Delta(B)_v} - (B_t + B_0)\right]\frac{p_0}{A_0}\right\}, \tag{150a}$$

$$= t_v + \frac{\Delta(B)_v}{100A_0}\,p_0\left\{1 + \left[\frac{\Delta(C')_v}{\Delta(B)_v} - (B_t + B_0)\right]\frac{p_0}{A_0}\right\}. \tag{151a}$$

Constant Pressure Gas Thermometer. For the constant pressure gas thermometer the mass of gas is constant and p is constant and has the value p_0. The following relations are useful:

$$p_0V = A + B\,p_0 + C\,p_0^2, \tag{152}$$

$$= A\left[1 + B\frac{p_0}{A} + (C' - B^2)\frac{p_0^2}{A^2}\right], \tag{153}$$

$$\frac{V}{V_0} = \frac{A}{A_0}\left\{1 + \left(\frac{B}{A} - \frac{B_0}{A_0}\right)p_0 + \left[\left(\frac{C}{A} - \frac{C_0}{A_0}\right) - \frac{B_0}{A_0}\left(\frac{B}{A} - \frac{B_0}{A_0}\right)\right]p_0^2\right\}, \tag{154}$$

$$= \frac{A}{A_0}\left\{1 + \left(\frac{B}{A} - \frac{B_0}{A_0}\right)p_0 + \left[\left(\frac{C'}{A^2} - \frac{C_0'}{A_0^2}\right) - \left(\frac{B^2}{A^2} + \frac{B\,B_0}{A\,A_0} - \frac{2B_0^2}{A_0^2}\right)\right]p_0^2\right\}, \tag{155}$$

$$\frac{V_0}{V} = \frac{A_0}{A}\left\{1 - \left(\frac{B}{A} - \frac{B_0}{A_0}\right)p_0 - \left[\left(\frac{C}{A} - \frac{C_0}{A_0}\right) - \frac{B}{A}\left(\frac{B}{A} - \frac{B_0}{A_0}\right)\right]p_0^2\right\}, \tag{156}$$

$$= \frac{A_0}{A}\left\{1 - \left(\frac{B}{A} - \frac{B_0}{A_0}\right)p_0 - \left[\left(\frac{C'}{A^2} - \frac{C_0'}{A_0^2}\right) - \left(\frac{2B^2}{A^2} - \frac{B\,B_0}{A\,A_0} - \frac{B_0^2}{A_0^2}\right)\right]p_0^2\right\}. \tag*{157)}$$

Substitution of the values of p_0V from Eqs. (152) and (153) into Eq. (11) gives:

$$\alpha = \alpha_p - \frac{B_{100} - B_0\,(1 + 100\alpha)}{100A_0}\,p_0\left\{1 + \left[\frac{C_{100} - C_0\,(1 + 100\alpha)}{B_{100} - B_0\,(1 + 100\alpha)} - \frac{B_0}{A_0}\right]p_0\right\}, \tag{158}$$

$$= \alpha_p - \frac{B_{100} - B_0\,(1 + 100\alpha)}{100A_0}\,p_0\left\{1 + \left[\frac{C'_{100} - C_0'\,(1 + 100\alpha)^2}{B_{100} - B_0\,(1 + 100\alpha)} - B_{100} - 2B_0\,(1 + 100\alpha)\right]\frac{p_0}{A_0\,(1 + 100\alpha)}\right\}. \tag{159}$$

Substitution of the values of p_0V into Eq. (14) gives:

$$t = t_p + \frac{T_0\Delta(B/T)}{100A_0}\,p_0\left\{1 + \left[100A_0\,\frac{\Delta(C/T)}{\Delta(B/T)} - T_0\,(B_{100} - B_0)\right]\frac{p_0}{100A_0}\right\}, \tag{160}$$

$$= t_p + \frac{T_0\Delta(B/T)}{100A_0}\,p_0\left\{1 + \left[100\,\frac{\Delta(C'/T^2)}{\Delta(B/T)} - 100\,\frac{\Delta(B^2/T^2)}{\Delta(B/T)} - (B_{100} - B_0)\right]\frac{T_0p_0}{100A_0}\right\}. \tag{161}$$

Eqs. (158) to (161) may be written:

$$\alpha = \alpha_p - \frac{B_{100} - B_0\,(1 + 100\alpha_p)}{100A_0}\,p_0\left\{1 + \frac{C_{100} - C_0\,(1 + 100\alpha_p)}{B_{100} - B_0\,(1 + 100\alpha_p)}\,p_0\right\}, \tag{158a}$$

$$= \alpha_p - \frac{B_{100} - B_0\,(1 + 100\alpha_p)}{100A_0}\,p_0\left\{1 + \left[\frac{C'_{100} - C_0'\,(1 + 100\alpha_p)^2}{B_{100} - B_0\,(1 + 100\alpha_p)} - B_{100} - B_0\,(1 + 100\alpha_p)\right]\frac{p_0}{A_0\,(1 + 100\alpha_p)}\right\}, \tag{159a}$$

$$t = t_p + \frac{T_0\Delta(B/T)_p}{100A_0}\,p_0\left\{1 + \frac{\Delta(C/T)_p}{\Delta(B/T)_p}\,p_0\right\}, \tag{160a}$$

$$= t_p + \frac{T_0\Delta(B/T)_p}{100A_0}\,p_0\left\{1 + \left[\frac{\Delta(C'/T^2)_p}{\Delta(B/T)_p} - \frac{\Delta(B^2/T^2)_p}{\Delta(B/T)_p}\right]\frac{T_0p_0}{A_0}\right\}. \tag{161a}$$

(*b*) *Correction from Joule and Joule-Thomson Coefficients*

Let η be the Joule coefficient and μ the Joule-Thomson coefficient of a gas:

$$\eta = -\left(\frac{\partial T}{\partial V}\right)_U = \frac{(\partial U/\partial V)_T}{(\partial U/\partial T)_V}, \tag{162}$$

$$\mu = \left(\frac{\partial T}{\partial p}\right)_H = -\frac{(\partial H/\partial p)_T}{(\partial H/\partial T)_p}; \tag{163}$$

and let $C_v = (\partial U/\partial T)_V$ and $C_p = (\partial H/\partial T)_p$ be the heat capacities at constant volume and constant pressure, respectively. Then λ,

$$\lambda \equiv \eta C_v, \tag{164}$$

can be used to correct α_v and t_v for the deviation of the thermometric gas from an ideal gas; and σ,

$$\sigma \equiv \mu C_p, \tag{165}$$

can be used to correct α_p and t_p. Since accurate experimental determinations of the Joule coefficient η have not been made, the quantity λ is computed from σ and compressibility data by use of the thermodynamic equation:

$$\lambda = -\sigma\left(\frac{\partial p}{\partial V}\right)_T - \left(\frac{\partial(pV)}{\partial V}\right)_T. \tag{166}$$

The partial derivatives in Eq. (166) may be evaluated from the equation of state (136).

Constant Volume Gas Thermometer. Let

$$\lambda \equiv \eta C_v = \left(\frac{\partial U}{\partial V}\right)_T = T\left(\frac{\partial p}{\partial T}\right)_V - p \equiv -\left[\frac{\partial(p/T)}{\partial(1/T)}\right]_V. \tag{167}$$

Thus

$$d\left(\frac{p}{T}\right) = -\lambda d\left(\frac{1}{T}\right); \qquad (V = \text{constant}) \tag{168}$$

and integration from 0° to 100° C. at constant volume gives:

$$\frac{p_{100}}{T_{100}} - \frac{p_0}{T_0} = -\int_{T_0}^{T_{100}} \lambda d\left(\frac{1}{T}\right), \qquad (V = V_0 = \text{constant}) \tag{169}$$

the integral being evaluated along the constant volume (or density) curve to which α_v refers (the density of the gas at p_0 and T_0). Substitution of the value of P_{100} obtained from Eq. (169) into Eq. (4) and use of Eq. (25) give:

$$\alpha = \alpha_v + \frac{1 + 100\alpha}{100\,\alpha p_0}\int_{T_0}^{T_{100}} \lambda d\left(\frac{1}{T}\right), \tag{170}$$

where p_0 and λ are to be expressed in the same units. In the first approximation the quantity α on the right hand side of the equation can be replaced by α_v or by the approximate value $\alpha = 0.003661$, T_0 taken to be 273.16, and λ expressed as a function of $(T_0 + t_v)$.

Integration of Eq. (168) from 0° to t° C. gives:

$$\frac{p_t}{T} - \frac{p_0}{T_0} = -\int_{T_0}^{T} \lambda d\left(\frac{1}{T}\right). \qquad (V = V_0 = \text{constant}) \tag{171}$$

Substitution of the value of p_t from Eq. (171) and p_{100} from Eq. (169) into Eq. (7) gives:

$$t = t_v + \frac{T_0}{100p_0}\left[100T\int_{T_0}^{T}\lambda d\left(\frac{1}{T}\right) - t_v\, T_{100}\int_{T_0}^{T_{100}}\lambda d\left(\frac{1}{T}\right)\right] \tag{172}$$

In the first approximation T can be replaced by $(T_0 + t_v)$, T_0 taken to be 273.16, and λ expressed as a function of $(T_0 + t_v)$.

It will be noted that λ can be computed from the equation of state parameters through Eq. (167). Thus from Eq. (136) we find:

$$\lambda = \frac{AT}{V^2}\left[\left(\frac{dB}{dT}\right) + \frac{1}{V}\left(\frac{dC'}{dT}\right)\right], \tag{173}$$

$$= -\frac{R}{V^2}\left[\frac{dB}{d\,(1/T)} + \frac{1}{V}\frac{dC'}{d\,(1/T)}\right]. \tag{174}$$

Constant Pressure Gas Thermometer. Let

$$\sigma \equiv \mu C_p = -\left(\frac{\partial H}{\partial p}\right)_T = T\left(\frac{\partial V}{\partial T}\right)_P - V \equiv -\left[\frac{\partial\,(V/T)}{\partial\,(1/T)}\right]_P. \tag{175}$$

Thus

$$d\left(\frac{V}{T}\right) = -\sigma d\left(\frac{1}{T}\right); \qquad (p = \text{constant}) \tag{176}$$

and integration from 0° to 100° C. at constant pressure gives:

$$\frac{V_{100}}{T_{100}} - \frac{V_0}{T_0} = -\int_{T_0}^{T_{100}}\sigma d\left(\frac{1}{T}\right), \qquad (p = p_0 = \text{constant}) \tag{177}$$

the integral being evaluated along the constant pressure curve, p_0, to which α_p refers. Substitution of the value of V_{100} from Eq. (177) into Eq. (11) and use of the relation (25) give:

$$\alpha = \alpha_p + \frac{1 + 100\alpha}{100\alpha\, V_0}\int_{T_0}^{T_{100}}\sigma d\left(\frac{1}{T}\right). \tag{178}$$

The quantity V_0 may be computed from T_0 and p_0 by Eq. (135), and is to be expressed in the same units as σ. The same approximation may be made as for Eq. (170).

Integration of Eq. (176) from 0° to t° C. gives:

$$\frac{V_t}{T} - \frac{V_0}{T_0} = -\int_{T_0}^{T}\sigma d\left(\frac{1}{T}\right). \qquad (p = p_0 \text{ constant}) \tag{179}$$

Substitution of the value of V_t from Eq. (179) and V_{100} from Eq. (177) into Eq. (14) gives:

$$t = t_p + \frac{T_0}{100V_0}\left[100T\int_{T_0}^{T}\sigma d\left(\frac{1}{T}\right) - t_p\, T_{100}\int_{T_0}^{T_{100}}\sigma d\left(\frac{1}{T}\right)\right]. \tag{180}$$

the same approximations may be made as for Eq. (172).

From Eq. (175) and the equation of state (135) we find:

$$\sigma = \left(T\frac{dB}{dT} - B\right) + \left(T\frac{dC}{dT} - C\right)p, \tag{181}$$

$$= -\left(\frac{d\,(B/T)}{d\,(1/T)} + \frac{d\,(C/T)}{d\,(1/T)}\,p\right). \tag{182}$$

At the present time no accurate experimentally determined Joule coefficients are available[7] and very few Joule-Thomson coefficients. The most accurate measurements of the latter type are those of Roebuck and his associates. Yet his values of λ for nitrogen computed from his measured μ coefficients, heat capacities, and compressibility data by Eq. (166) are obviously in disagreement with all of the compressibility data in the temperature range 0° to 100° C. since he finds from his computations[8] that the values of the Kelvin Temperature of the ice-point calculated from our measured thermometric coefficients α_v and his λ values show a trend with ice-point pressure p_0. No such trend[9] is evident when the corrections to zero pressure are made with the second virial coefficients, B_0 and B_{100}, for nitrogen determined by Henning and Heuse, Keesom and Tuyn, or Keyes.[10]

The best way to utilize Joule-Thomson coefficients for the correction of α_v, t_v, α_p, and t_p is probably the method proposed by Keyes,[10] in which he computes second virial coefficients, B, from the Joule-Thomson coefficients and heat capacities, and thus is able to average the results of the measurements of Joule-Thomson coefficients with those of compressibility measurements.

8. SUMMARY OF OBSERVATIONS, DATA, AND FORMULAE FOR CORRECTION OF THE MEASUREMENTS FOR A CONSTANT VOLUME GAS THERMOMETER

(a) *Quantities Measured in Each Run*

H = vertical distance (mm.) from crown of mercury meniscus in short arm of main manometer to crown in long arm.

h_1 = height (mm.) of mercury meniscus in long arm of main manometer.

h_2 = height (mm.) of meniscus in short arm of main manometer.

h_3 = vertical distance (mm.) from crown of meniscus in short arm of main manometer to index mark in short arm.

t_s = mean temperature (° C. Int.) of the scale.

t_{Hg} = mean temperature (° C. Int.) of mercury in main manometer.

t_b = mean temperature (0° C. Int.) of main thermometer bulb.

t_r = nominal integral temperature (° C. Int.) of the run.

t_i = mean temperature (° C. Int.) of the i-th dead space of the main thermometer system ($i = 1, 2, 3, \ldots m$).

H_a = vertical distance (mm.) from crown of mercury meniscus in short arm of auxiliary manometer to crown in long arm.

t_{Hga} = mean temperature (° C. Int.) of mercury in auxiliary manometer.

t_{da} = mean temperature (° C. Int.) of the dead space of the auxiliary thermometer.

H_e = vertical height (mm.) of mercury column in external manometer.

H_B = vertical height (mm.) of mercury column in barometer.

t_e = mean temperature of mercury in external manometer and barometer (mean room temperature).

(b) *Calibration Quantities*

ε = scale error (mm.); a function of H for a fixed value of D_2.

D_2 = scale division nearest index mark in short arm of main manometer.

d_1 = diameter (mm.) of long arm of main manometer; a function of H for a fixed value of D_2.

d_2 = diameter (mm.) of short arm of main manometer at index mark; a constant.

a_m = area (ml./mm.) of short arm of main manometer at index mark.

V_{bn} = volume (ml.) of main thermometer bulb under standard conditions.

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[7] See, for instance, F. G. Keyes and F. W. Sears, Proc. Nat. Acad. Sci., **11,** 38–41 (1925); J. R. Roebuck, Proc. Am. Acad. Arts Sci., **64,** 287–334 (1930), see p. 312; E. W. Washburn, Bur. of Stan. J. Res. **9,** 521–528 (1932).

[8] J. R. Roebuck and T. A. Murrell, *Temperature,* pp. 60–73, Reinhold Publishing Corp., New York, 1941.

[9] J. A. Beattie, *Temperature,* pp. 74–88, Reinhold Publishing Corp., New York, 1941.

[10] W. Heuse and J. Otto, Ann. der Physik (5) **2,** 1012–1030 (1929); W. H. Keesom and W. Tuyn, Kamerlingh Onnes Lab., Univ. of Leiden, Supplement No. **78,** 85 pp. (1936); F. G. Keyes, *Temperature,* pp. 45–59, Reinhold Publishing Corp., New York, 1941.

V_{in} = volume (ml.) of i-th main thermometer dead space under standard conditions ($i = 1, 2, 3, \ldots m$). V_{mn} is the volume in the short arm above a horizontal plane through the index mark plus Δ.

l_{bn} = vertical distance (mm.) from center of main thermometer bulb to the beginning of the first dead space under standard conditions.

l_{in} = vertical height (mm.) of the i-th dead space of the main thermometer system under standard conditions ($i = 1, 2, 3, \ldots m$). The algebraic sign of l is plus if the end nearer the bulb is below the farther end, otherwise minus.

δ_a = mean capillary depression correction for the auxiliary manometer.

r_{an} = ratio of volume of the dead space to the total volume of the auxiliary thermometer under standard conditions.

$\Phi_{an} = p'_{an}\left[\frac{1 - r_{an}}{T_{ban}} + \frac{r_{an}}{T_{dan}}\right]$ = calibration function for auxiliary thermometer. In this expression T_{ban} is the Kelvin temperature of the bulb of the auxiliary thermometer, T_{dan} the mean Kelvin temperature of the dead space, and p'_{an} the pressure in the calibration run.

g_l = acceleration of gravity (cm./sec.^{2}) at the laboratory.

R_0, α, δ, = ice point resistance and parameters in the Callendar equation for the platinum resistance thermometers.

(c) *Properties of Materials*

α_s = mean coefficient of linear thermal expansion (° C.$^{-1}$ Int.) of the material of the scale from t_{sn} to t_s.

ρ_s = density (gm./mm.^{3}) of the material of the scale.

E_s = Young's modulus (dynes/mm.^{2}) of the material of the scale.

δ = capillary depression (mm.) of the mercury in the main manometer.

α_{Hg} = mean coefficient of thermal dilation (° C.$^{-1}$ Int.) of mercury from 0° to $t°_{Hg}$ C.

β_{Hg} = mean coefficient of cubical compressibility (atm.$^{-1}$) of mercury from 0 to 3 atm. at mean room temperature.

$F = \frac{g_l}{g_n}\,\frac{1}{1 + \alpha_{Hg} t_{Hg}}$.

g_n = standard gravity, 980.665 cm./sec.^{2}

V_c = covolume (ml.) of mercury meniscus.

α_b = mean coefficient of thermal dilation (° C.$^{-1}$ Int.) of the material of the bulb of the main thermometer from $t°_{bn}$ to t_r° C.

α'_b = true coefficient of thermal dilation (° C.$^{-1}$ Int.) of the material of the bulb at t_r° C.

$\frac{\beta_b}{760}$ = mean coefficient of cubical compressibility (mm.$^{-1}$) of the material of the bulb from 0 to 3 atm. at t_r° C.

γ_b = mean dilation (ml./mm.) of the bulb due to difference between internal and external pressure at t_r° C.

α_i = mean coefficient of thermal dilation (° C.$^{-1}$ Int.) of the material of the i-th dead space of the main thermometer system from t_{in} to t_i° C. ($i = 1, 2, 3, \ldots m$).

α_v = mean coefficient of thermal pressure increase (° C.$^{-1}$ Int.) at constant volume from 0° to 100° C. of the thermometric gas. This value need be known only approximately.

M = molecular weight of the gas.

B = second virial coefficient (ml./mole) of the gas.

Subscript n denotes standard conditions.

(d) *Equations*

For the auxiliary thermometer. $p_a' = (H_a + \delta_a)\,F_a$

$$\frac{1}{T_1} = \frac{\dfrac{\Phi_{an}}{p'_a} - \dfrac{r_{an}}{T_{da}}}{1 - r_{an}}$$

For the external pressure control circuit. $p_e = (H_c + H_B)\,F_e$

$$p' - p_e = HF - (H_c + H_B)\,F_e$$

For the main thermometer. $p' = (H + \delta_1 - \delta_2 + \delta_3)\,F$

$$\delta_3 = \varepsilon_1 - \varepsilon_2 + \alpha_s H\,(t_s - t_{sn}) + \frac{\rho_s\,g_l}{2E_s}\,H\,(H + 2D_2) + \beta_{Hg}\,H\,\frac{HF - 760}{1520}$$

$$p = p' + \delta_4 + \delta_5 + \delta_6 + \delta_7 + \delta_8$$

$$\delta_4 = 1.1795 \times 10^{-6} M\,\frac{p' V_b}{V}\left(\frac{l_b}{T_b} + \sum_1^m{}_i\,\frac{l_i}{T_i}\right)$$

$$\delta_5 = \frac{p'}{V}\left[(V_b - V_{bn}) + \sum_2^m{}_i\,(V_i - V_{in})\right]$$

$$\delta_6 = \frac{p'}{V}\left[V_{1n}\left(\frac{T_b}{T_1} - 1\right) + \sum_2^m{}_i\,V_1\left(\frac{T_b}{T_i} - 1\right)\right]$$

$$\delta_7 = \frac{p'^2}{RV}\left[B_r\left(\frac{V_b - V}{T_r} + 2\sum_1^m{}_i\,\frac{V_i}{T_i}\right) - T_r\sum_1^m{}_i\,\frac{B_i\,V_i}{T_i^2}\right]$$

$$\delta_8 = p_0\,\alpha_v\,(t_r - t_b)$$

$$V = V_{bn} + \sum^m{}_i\,V_{in}$$

$$V_b - V_{bn} = V_{bn}\left[\alpha_b\,(t_r - t_{bn}) + \alpha_b'\,(t_b - t_r) - \frac{\beta_b}{760}\,(p' - 760)\right] + \gamma_b\,(p' - p_e)$$

$$V_i - V_{in} = V_{in}\,\alpha_i\,(t_i - t_{in}) \qquad (i = 2, 3, 4, \ldots\ m - 1)$$

$$V_m - V_{mn} = V_{mn}\,\alpha_m\,(t_m - t_{mn}) + \Delta V_m$$

$$\Delta V_m = a_m\,h_3 + V_c - \Delta.$$

Δ = a number slightly less than the smallest value of $a_m\,h_3 + V_c$.

$T = t + T_0 + (T_{\text{abs.}} - T_{\text{Int.}})$; $t \equiv t°$ C. (Int.)

l_b and l_i ($i = 1, 2, 3, \ldots\ m$) depend on l_{bn} and l_{in}, $(t_b - t_{bn})$ and $(t_i - t_{in})$, $\alpha_b/3$ and $\alpha_i/3$, and the method of suspension of the bulb of the main thermometer; l_m also depends on h_3.

(c) *Tabulated Values*

F as a function of t_{Hg}.

δ_1 as a function of H and h_1.

δ_2 as a function of h_2.

δ_3 as a function of H and t_s

$\delta\left(\frac{t}{100}\right)\left(\frac{t}{100} - 1\right)$ as a function of t_{Pt} for the five platinum resistance thermometers used to determine t_{Hg} and t_m.

Critical tables giving V_i and $V_i - V_{in}$ as functions of t_i ($i = 2, 3, 4, \ldots\ m$).

$V_c - \Delta$ as a function of h_2.

$V_{bn}\,\alpha_b\,t_r$ as a function of t_r.

$V_{bn}\,\alpha_b'$ as a function of t_r.

$V_{bn}\,\beta_b/760$ as a function of t_r.

γ_b as a function of t_r.

l_b/T_b as a function of t_r.

l_1/T_1 as a function of $1/T_1$.

l_i/T_i as a function of t_i and t_r ($i = 2, 3, 4, \ldots\ m - 1$).

l_m/T_m as a function of t_m and h_3.

$T°$ Kelvin as a function of $t°$ C. Int.

B as a function of t.

9. SUMMARY

The idealized constant volume and constant pressure gas thermometers are defined and the relations for the thermometric coefficients and gas temperatures given in terms of these definitions.

The deviations of the practical from the idealized gas thermometers are discussed and relations given for correction of the observations on the practical instrument for the deviations from ideality.

The complete theory of the use of the auxiliary gas thermometer for determination of the dead space correction in the region of large thermal gradient is given, and a test of the performance of the auxiliary thermometer is discussed.

Relations for the correction of the observed thermometric coefficients and gas temperatures for the imperfection of the thermometric gas are given.

(Contribution from the Research Laboratory of Physical Chemistry,
Massachusetts Institute of Technology, No. 471)

AN EXPERIMENTAL STUDY OF THE ABSOLUTE TEMPERATURE SCALE

VIII. THE THERMAL EXPANSION AND COMPRESSIBILITY OF VITREOUS SILICA AND THE THERMAL DILATION OF MERCURY

By James A. Beattie, B. Edwin Blaisdell, Joseph Kaye, Harold T. Gerry, and Clarence A. Johnson

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1. Introduction

In the reduction of the data resulting from gas thermometric measurements an accurate knowledge of the dilation of the bulb caused by variations in temperature and in internal and external pressure is required. We used bulbs of vitreous silica[1] because of the low thermal dilation of this material.

In order to record the thermal dilation of the bulbs in terms of that of mercury, we determined the apparent thermal dilation of mercury in the two vitreous silica bulbs used by us over the temperature range 0° to 350° C. At the same time the dilation of the bulbs caused by a difference between inside and outside pressure was measured at several temperatures. Later a cylindrical ring of vitreous silica was prepared from one of the bulbs and its linear thermal expansion in the temperature range − 200° to + 450° C. determined by an interference method. From these results and data on the rigidity of vitreous silica, it was possible to compute the mean coefficient of linear thermal expansion and mean coefficient of compressibility of vitreous silica, and the mean coefficient of thermal dilation of mercury. These results are compared with those of other investigators in Tables III, VI, and IX. Equations expressing these quantities as functions of temperature are given in the Summary, and these and derived quantities are tabulated for various temperatures in Tables X to XVIII.

2. Description of the Apparatus

(a) *Apparent Thermal Dilation of Mercury*

A sketch of one of the bulbs is shown in Fig. 1. The bulbs, designated as "Red" and "Green," were the two used in the final gas thermometric measurements[1] (Runs 111 to 394) and each had a volume of about 1000 ml. The pyrex capillary and graded seal attached to the bulb in the earlier measurements were replaced by a vitreous silica capillary of about 0.9 mm. bore. The welded steel case surrounding the bulb was fitted with a three-piece steel liner accurately shaped to fit the external surface of the bulb with a clearance of 0.5 mm. and a push fit in the case. The connection between the silica capillary and metal tube at the top was made by means of a heavy rubber tube. The left-hand side arm near the top of the metal tube was for the introduction of mercury into the case and the application of gas pressure or suction; and the right-hand tube was for the overflow of mercury from the case. The numbers are distances in centimeters measured from the top of the thermostat cover.

The tip of the silica capillary was placed beneath the surface of mercury in a weighing bottle

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[1] J. A. Beattie, D. D. Jacobus, J. M. Gaines, Jr., M. Benedict, and B. E. Blaisdell, Proc. Am. Acad. Arts Sci., **74,** 327-342 (1941).

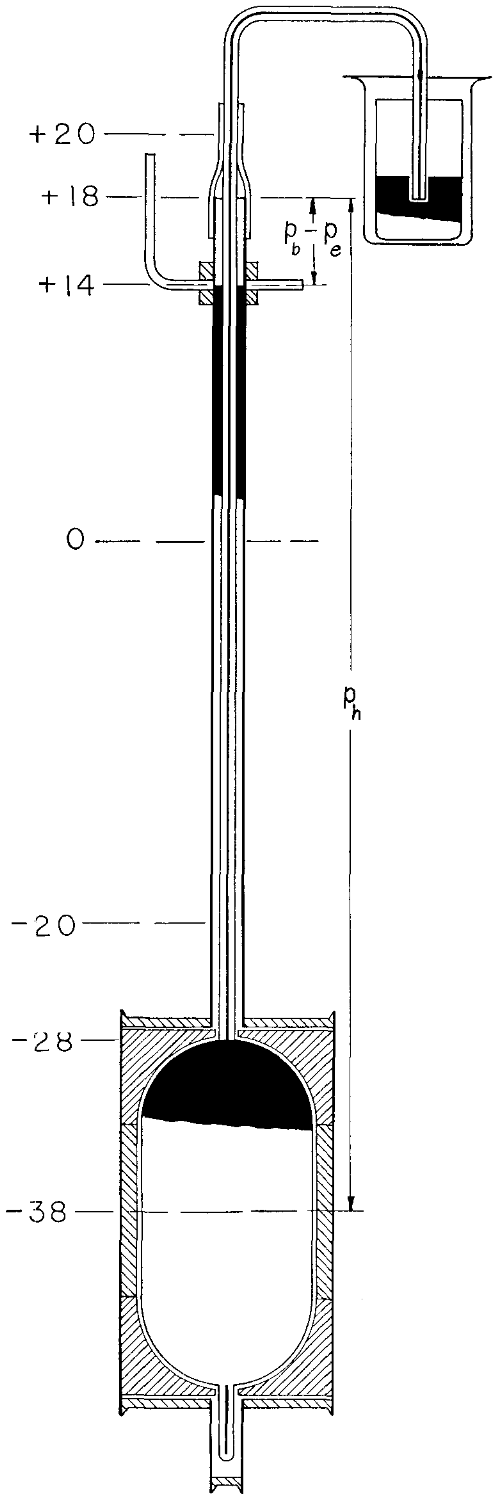

Fig. 1. Sketch of the apparatus. The numbers are the distances in centimeters measured from the top of the thermostat cover.

held in a beaker which had a fairly tight-fitting cover that effectively prevented circulation of air but not equilibration of pressure between outside and inside.

The bulb floated in a bath of mercury contained in the metal case and always made contact with the upper hemispherical surface of the liner.

(b) *Linear Thermal Expansion of Vitreous Silica*

A cylindrical ring of vitreous silica 3 cm. in diameter, 2 cm. long and 2 mm. thick (the thickness of the bulb) was made from the Green bulb and annealed in the same manner as the bulbs. The change in length of the sample with change in temperature was measured by the absolute Fizeau method with a Pulfrich interferometer manufactured by Zeiss. In this method the sample itself is used to separate the top and bottom reflecting plates. Because of the large separation of the plates the intensity of the bands is low. The intensity was increased to a satisfactory visibility by sputtering the reflecting surfaces with platinum. In order to decrease the chance of relative motion of the sample and plates, the top plate was held down by a 50 gram weight. The source of light was the mercury green line for which $\lambda = 54.6224 \times 10^{-6}$ cm. in vacuo and in the helium of the density used in our experiments.

The thermostats were gas-tight and contained helium at a pressure of 2 mm. of mercury at room temperature. In one thermostat the expansion in the range − 200° to + 100° C. was studied; in a second that in the range 25° to 450° C. investigated.

The true length of the cylinder at 0° C. was $l_0 = 1.9368$ cm.

3. PROCEDURE

(a) *Apparent Thermal Dilation of Mercury*

The bulbs and cases were evacuated for several days while at a temperature of 400° C., and both were then filled in vacuo with mercury that had been distilled twice in air at 20 mm. pressure and once in vacuo. The mercury entered the systems through barometric columns and fell through two meters of tubing bent in a spiral.

The two bulbs and four standard platinum resistance thermometers were placed in the oil bath used in the gas thermometric measurements. The upper ends of the silica capillaries were placed beneath the surface of mercury in the weighing bottles and the system maintained overnight at a temperature close to the desired value. In the morning the system was brought to the desired temperature and automatic regulation maintained for one hour. The weighing bottle was replaced by a second bottle and the mass of mercury in the first computed from weighings made in air against brass standards. After one half an hour the second bottle was weighed to determine the gain or loss of mercury. The variation in the mass of mercury in the second bottle was less than 5×10^{-4} gm. in all runs.

The thermostat temperature was then changed to a new value and the process repeated.

In the oil bath runs were made from 0° to 150° C. The bulbs and resistance thermometers were then transferred to the nitrate bath and runs from 150° to 350° C. made. In each series most of the temperatures were approached from above and from below. In the low temperature series the temperature 152.315° was used unintentionally instead of 150° C. In the nitrate bath runs were made at both temperatures.

When the weighing bottle was removed the mercury ran back into the silica capillary for a short distance. The position of the meniscus was reproducible to ± 1 mm. in most cases and no correction was made for this effect when the position was thus reproduced. For several of the runs in succession the position of the meniscus differed appreciably from the normal position and a tip correction was applied. The normal position was resumed after the tip of the capillary had been cleansed by being raised to white heat.

At each temperature (but not for each run) the temperature distribution along the capillary in the region of large thermal gradient was determined by a thermocouple.

At 25°, 100°, 200°, and 300° C. the dilation of the bulb caused by a variation of external pressure, internal pressure being constant, was determined. The tip of the silica capillary was placed beneath the surface of mercury and suction applied to the case until the pressure at the side arm as indicated on an open manometer was about 700 mm. below atmospheric. The weighing bottle was replaced by an empty one and the pressure adjusted until the drop of mercury protruding from the capillary was 0.40 mm. high. The pressure in the side arm was then raised to about atmospheric and again adjusted until the drop had the same height. The mass of mercury forced out of the bulb was determined. Four determinations were made at each temperature.

(b) *Linear Thermal Expansion of Vitreous Silica*

The cylindrical ring of vitreous silica was placed in the thermostat with the reflecting plates top and bottom and a metal cylindrical ring weighing 50 gms. placed on the top plate. The necessary adjustments for proper reflection into the interferometer were made. The thermostat chamber was closed gas-tight and filled with helium to a pressure of 2 mm. at room temperature.

The thermostat was regulated automatically[1] at some temperature; and after one hour of satisfactory regulation (± 0.005° C.) the temperature and the micrometer reading for the index circle and the two bands on each side were determined. The process was repeated at other temperatures, the number of bands passing by the index circle during change in temperature being counted.

Temperatures were determined by platinum resistance thermometers: those below 0° C. were transferred to the absolute scale by comparison of the readings of the resistance thermometer with the indications of a constant volume hydrogen gas thermometer; and those above 0° C. were on the International Scale.

The band reading of the index was computed to 0.01 band by the method of least squares. Plots of band readings against temperature showed discontinuities at several places indicating that slipping of the plates or sample had occurred. Thus although all of the low temperature and all of the high temperature runs were each made in one continuous series, it was necessary to treat each set as several series.

4. DERIVATION OF THE EQUATIONS

Let: p = pressure (in atm. unless otherwise stated).

V = volume (ml.).

t = Centigrade temperature (° C. Int. unless otherwise stated).

M = grams of mercury.

δ = density (gm./ml.).

Subscript Hg denotes that the quantity applies to mercury.

Subscript b denotes the bulb.

Subscript i ($i = 1, 2, 3, \ldots m$) denotes the i-th section of the capillary.

Subscript w denotes the weighing bottle.

Subscript 0 denotes the value of a quantity at the standard conditions of calibration 0° C. and 1 atm. pressure.

Subscript r denotes the nominal (integral) International temperature of the thermostat for a run. Thus if $t_b = 150.0018°$, $t_r = 150°$ C.

p_e = external pressure on the bulb in a plane passing horizontally through the center.

p_h = pressure caused by head of mercury (see Fig. 1).

p_B = corrected barometric pressure.

α = mean coefficient of thermal dilation, $(1/V_0)\,(\Delta V/t)°$ C.$^{-1}$, from 0° to t_i° C. for the capillary sections and the contained mercury, and from 0° to t_r° C. for the bulb and contained mercury, pressure being 1 atm.

α' = true coefficient of thermal dilation, $(1/V_0)$ $(dV/dt)°$ C.$^{-1}$, at t_r° C. and 1 atm. pressure.

β = mean coefficient of compressibility, $-(1/V_{t_r})\,(\Delta V/\Delta p)$ atm.$^{-1}$, at low pressure and at t_r° C. where V_{t_r} is the volume at t_r° C. and 1 atm.

γ = mean dilation, $\Delta V_b/(p_b - p_e)$ ml. atm.$^{-1}$, of the bulb at t_r caused by the difference between internal pressure p_b and external pressure p_e.

$C_b = \delta_{Hg0}\,\gamma_b/(1 + \alpha_{Hg}\,t_r)$ gm. Hg atm.$^{-1}$ = grams of mercury forced out of the bulb per atmosphere increase in $p_b - p_e$ at t_r. We measured C_b and computed γ_b from the above equation.

The volume V_b of the bulb at (t_b, p_b, p_e) is given by the expression:

$$V_b = V_{b0}\,[1 + \alpha_b t_r + \alpha_b'\,(t_b - t_r)] \times [1 - \beta_b\,(p_b - 1)] + \gamma_b\,(p_b - p_e); \quad (1)$$

and the density of the mercury in the bulb by the equation:

$$\delta_{Hg} = \delta_{Hg0}\,[1 + \alpha_{Hg}\,t_r + \alpha'_{Hg}\,(t_b - t_r)]^{-1} \times [1 - \beta_{Hg}\,(p_b - 1)]^{-1} \quad (2)$$

The volume of the i-th section of capillary at t, assumed independent of pressure, is

$$V_i = V_{i0}\,(1 + \alpha_i\,t_i); \quad (i = 1, 2, 3, \ldots m) \quad (3)$$

and the density of mercury in the i-th capillary is taken to be

$$\delta_{Hg} = \delta_{Hg0}\,(1 + \alpha_{Hg}\,t_i), \quad (4)$$

independent of pressure.

The total mass of mercury in the system (bulb, capillary, weighing bottle) is constant for a complete series of runs. At any bulb temperature, t_b, this mass is:

$$M = M_{b0}\,\frac{[1+\alpha_b t_r+\alpha_b'(t_b-t_r)]\,[1-\beta_b(p_b-1)]}{[1+\alpha_{Hg}t_r+\alpha'_{Hg}(t_b-t_r)]\,[1-\beta_{Hg}(p_b-1)]} + C_b(p_b-p_e) + \sum_1^m{}_i\,M_{i0}\,\frac{1+\alpha_i t_i}{1+\alpha_{Hg}t_i} + M_{wt_b} \quad (5)$$

$$= M_{b0}\,\frac{1+\alpha_b t_r}{1+\alpha_{Hg}t_r} + \sum_1^m{}_i\,M_{i0} + M_{wt_r}; \quad (6)$$

where

$$M_{wt_r} = M_{wt_b} + \Delta M_{bt_b} + \sum_1^m{}_i\,\Delta M_{it_i}, \quad (7)$$

$$\Delta M_{bt_b} = M_{b0}\left\{\frac{\alpha'_b\,(1+\alpha_{Hg}t_r) - \alpha'_{Hg}(1+\alpha_b t_r)}{(1+\alpha_{Hg}t_r)^2} \times (t_b-t_r) + \frac{1+\alpha_b t_r}{1+\alpha_{Hg}t_r}\,(\beta_{Hg}-\beta_b)\,(p_b-1)\right\} + C_b\,(p_b-p_e), \quad (8)$$

$$\Delta M_{it_i} = M_{i0}\,\frac{t_i\,(\alpha_i-\alpha_{Hg})}{1+\alpha_{Hg}t_i}. \quad (i = 1, 2, 3, \ldots m) \quad (9)$$

In the above expressions M_{b0} and M_{i0} are the number of grams of mercury of standard density —13.59546 gms./ml.—in the bulb and the i-th capillary section, respectively, when each is at 0° C. and under 1 atm. internal and external pressure; M_{wt_b} is the actual number of grams of mercury in the weighing bottle when the bulb is at t_b and the capillary sections at t_i; and M_{wt_r} is the corrected number of grams of mercury which would have been in the weighing bottle if: (1) the bulb temperature had been t_r, (2) the external and internal pressures had been constant throughout the system and had had the value 1 atm., and (3) the capillary sections 1 to m had been at 0° C. and 1 atm. pressure (thus containing the same mass of mercury at all bulb temperatures).

The approximations made in deriving the above equations introduce an error of less than $.1 \times 10^{-5}$ grams of mercury.

Applying equation (6) to $t_r = 0$ and $t_r = t$ and equating the two values of M, we obtain:

$$\alpha_{Hg} = \frac{m}{t\,(M_{b0}-m)} + \frac{M_{b0}\,\alpha_b}{M_{b0}-m}, \quad (10)$$

where

$$m = M_{wt} - M_{w0} \quad (11)$$

is the corrected number of grams of mercury that flows into the weighing bottle when the bulb is heated from 0° to t° C. The quantity

$$\alpha_{Hg}\ (\text{apparent}) = \frac{m}{t\,(M_{b0}-m)} \quad (12)$$

is called the apparent mean coefficient of thermal dilation of mercury in the material composing the bulb.

5. RESULTS

(a) *Linear Thermal Expansion of Vitreous Silica*

The band reading was multiplied by $10^6\lambda/2l_0$ ($= 10^6 \times 54.6224 \times 10^{-6}/2 \times 1.9368 = 14.1012$) to give $[10^6\ (l - a)/l_0]_{\text{obsd.}}$, the length of the sample (in units of $10^6/l_0$) at the temperature t, except for the parameter a that is constant for any one series of runs, but varies from series to series on account of the slippage. All of the values of $[10^6\ (l - a)/l_0]_{\text{obsd.}}$ were plotted against t on a single plot, the pieces of the curves corresponding to different series being moved as a whole parallel to the length axis until a single curve could be drawn through all of the series of points. From points read from this curve an equation similar to Eq. (A), Table I, was derived expressing $[10^6\ (l - l_0)/l_0]_{\text{obsd.}}$ as a function of t. The values $[10^6\ (l - l_0)/l_0]_{\text{calcd.}}$ were computed from this equation for each temperature at which a measurement was made. We determined a for each series as

$$10^6\ (a - l_0)/l_0 = \frac{\Sigma\,[10^6\ (l - l_0)/l_0]_{\text{calcd.}} - \Sigma\,[10^6\ (l - a)/l_0]_{\text{obsd.}}}{\text{number of measurements in series}}.$$

Hence:

$$[10^6\ (l - l_0)/l_0]_{\text{obsd.}} = [10^6\ (l - a)/l_0]_{\text{obsd.}} + 10^6\ (a - l_0)/l_0.$$

Thus a was determined from all of the measurements in any one series and not alone from the observations near 0° C.

The values of $[10^6\ (l - l_0)/l_0]_{\text{obsd.}}$ so derived were again expressed as a function of t; and new, slightly different, values of a obtained. The process was repeated a third time, no significant difference in the values of a being found.

The results are given in Table I. In the first column are listed the temperatures on the thermodynamic scale when below 0° C. and on the International scale when above 0°; in the second are given the observed values of $10^6\ (l - l_0)/l_0$ obtained as described above; and in the third the value computed from Eq. (A).

TABLE I

LINEAR THERMAL EXPANSION OF VITREOUS SILICA

$$10^6 \times (l - l_0)/l_0\ (\text{calcd.}) = \frac{t^2 + 157.361t}{0.00126792t^2 + 0.88121t + 412.109} \qquad (-175° < t°\ \text{C.} < +450°) \qquad \text{(A)}$$

$$10^6 \times (V - V_0)/V_0 = \frac{t^2 + 157.281t}{0.0004225t^2 + 0.29362t + 137.32} \qquad (-175° < t°\ \text{C.} < +450°) \qquad \text{(B)}$$

Temp.[1]	$10^6 \times (l - l_0)/l_0$			Temp.[1]	$10^6 \times (l - l_0)/l_0$			Temp.[1]	$10^6 \times (l - l_0)/l_0$		
°C.	Obsd.	Calcd.	Obsd.-calcd.	°C.	Obsd.	Calcd.	Obsd.-calcd.	°C.	Obsd.	Calcd.	Obsd.-calcd.
		Low Temperature Measurements									
	Series A1			− 76.37	−16.894	−17.562	+0.668	−157.09	− 0.591	− 0.140	−0.451
+ 26.14	+11.666	+11.001	+0.665	− 55.99	−15.624	−15.476	−0.148	−189.28[2]	+20.419	+20.780	−0.361
− 8.65	− 3.564	− 3.179	−0.385	− 28.82	− 9.844	− 9.554	−0.290	−218.49[2]	+43.259	+47.683	−4.424
− 40.60	−12.584	−12.527	−0.057	− 4.02	− 1.804	− 1.509	−0.295	−190.02[2]	+20.559	+21.367	−0.808
− 88.05	−17.804	−17.723	−0.081	+ 23.63	+10.466	+ 9.863	+0.603	−168.33	+ 6.039	+ 6.161	−0.122
−117.63	−13.574	−14.336	+0.762	+ 53.27	+24.986	+24.252	+0.734	−132.12	− 9.761	−10.493	+0.732
−142.93	− 7.514	− 6.610	−0.904	+ 82.35	+39.936	+40.019	−0.083	−102.41	−15.821	−16.790	+0.969
−186.42[2]	+16.886	+18.559	−1.673		Series A3			− 64.22	−16.241	−16.581	+0.340
−216.01[2]	+41.566	+45.097	−3.531	+107.45	+55.109	+54.569	+0.540	− 79.56	−19.211	−17.684	−1.527
	Series A2			+ 82.95	+40.299	+40.358	−0.059	− 65.39	−17.371	−16.710	−0.661
−195.61[2]	+22.456	+25.956	−3.500	+ 53.55	+22.959	+24.397	−1.438	− 10.42	− 4.541	− 3.799	−0.742
−177.81[2]	+10.186	+12.304	−2.118	− 11.30	− 3.131	− 4.102	+0.971	+ 45.85	+20.979	+20.469	+0.510
−155.88	− 1.094	− 0.756	−0.338	− 80.57	−18.921	−17.711	−1.210	+ 99.28	+50.169	+49.755	+0.414
−125.67	−14.214	−12.392	−1.822	−105.55	−15.821	−16.411	+0.590	+ 12.70	+ 4.909	+ 5.100	−0.191
− 97.03	−16.324	−17.292	+0.968	−127.22	−11.031	−11.963	+0.932	+ 13.95	+ 6.039	+ 5.628	+0.411

[1] Degrees C. absolute below 0°; degrees C. International above 0°.

[2] Points not used in fitting the equation; deviations not included in averages.

TABLE I—*Continued*

High Temperature Measurements

	Series B1		
25	10.577	10.482	+0.095
50	23.197	22.572	+0.625
75	35.997	35.908	+0.089
100	49.367	50.177	−0.810
	Series B2		
75	36.337	35.908	+0.429
100	50.547	50.177	+0.370
50	22.927	22.572	+0.355
25	9.327	10.482	−1.155
	Series B3		
50	21.440	22.572	−1.132
150	80.360	80.486	−0.126
250	143.960	143.103	+0.857
350	203.740	202.747	+0.993
450	255.940	256.533	−0.593
	Series B4		
150	80.398	80.486	−0.088
100	49.198	50.177	−0.979
250	142.788	143.103	−0.315
300	174.598	173.553	+1.045
200	112.648	111.838	+0.810
250	142.628	143.103	−0.475
	Series B5		
50	23.014	22.572	+0.442
350	202.304	202.747	−0.443
	Series B6		
200	111.759	111.838	−0.079
400	229.009	230.443	−1.434
300	173.169	173.553	−0.384
150	80.339	80.486	−0.147
400	231.119	230.443	+0.676
100	51.009	50.177	+0.832
200	110.839	111.838	−0.999
50	23.499	22.572	+0.927
350	203.459	202.747	+0.712
150	78.839	80.486	−1.647
150	79.829	80.486	−0.657
200	111.219	111.838	−0.619
350	203.609	202.747	+0.862
400	231.479	230.443	+1.036
450	257.459	256.533	+0.926
	Series B7		
100	50.486	50.177	+0.309
350	201.876	202.747	−0.871
300	173.036	173.553	−0.517
400	230.696	230.443	+0.253
250	142.806	143.103	−0.297
50	24.066	22.572	+1.494
100	50.566	50.177	+0.389
300	173.756	173.553	+0.203
450	255.566	256.533	−0.976

Series	Number of points	Average deviation	Root-mean-square deviation
A	35	0.618×10^{-6}	0.7496×10^{-6}
B	45	0.655×10^{-6}	0.7634×10^{-6}
A+B	80	0.638×10^{-6}	0.7574×10^{-6}

TABLE II

DEVIATIONS OF THE OBSERVED FROM THE CALCULATED VALUES OF THE LINEAR THERMAL EXPANSION OF VITREOUS SILICA FROM 0° TO t° C.

THE RESULTS ARE DERIVED FROM TABLE I

Temp. °C.	Number of Points	Obsd. minus calcd. Values of $\frac{l - l_0}{l_0} \times 10^6$			
		Sum of Positive	Sum of Negative	Algebraic Sum	Algebraic Average
		Low Temperature Measurements			
−175 to −125	7	1.664	3.637	−1.973	−0.282
−125 to − 75	8	3.957	2.818	+1.139	+0.142
− 75 to − 25	5	0.340	1.156	−0.816	−0.163
− 25 to + 25	6	1.382	1.613	−0.231	−0.038
+ 25 to + 75	5	2.512	1.438	+1.074	+0.215
over + 75	4	0.954	0.142	+0.812	+0.203
		High Temperature Measurements			
25	2	0.095	1.155	−1.060	−0.530
50	6	3.843	1.132	+2.711	+0.452
75	2	0.518	0.000	+0.518	+0.259
100	6	1.900	1.789	+0.111	+0.018
150	5	0.000	2.665	−2.665	−0.533
200	4	0.810	1.697	−0.887	−0.222
250	4	0.857	1.087	−0.230	−0.058
300	4	1.248	0.901	+0.347	+0.087
350	5	2.567	1.314	+1.253	+0.251
400	4	1.965	1.434	+0.531	+0.133
450	3	0.926	1.560	−0.634	−0.211
Arithmetic average					0.223

TABLE III

COMPARISON OF OUR VALUES OF THE MEAN COEFFICIENT OF LINEAR THERMAL EXPANSION FROM 0° TO *t*° C. OF VITREOUS SILICA WITH THE MEASUREMENTS AND THE SELECTED VALUES OF OTHER AUTHORS

$10^8\,\alpha$ (linear) $= a + bt + ct^2$				
Author	a	$b \times 10^2$	$c \times 10^4$	Range of validity (° C.)
Chappuis (1903)	38.474	11.5		0 to 83
Donaldson (1912)	38	11		0 to 30
Callendar (1913 A)	29	25	−7	− 20 to +150
Scheel (1914)	36.2	18.13	−3.40	−253 to +100
Scheel (1921)	39.5	12.82	−1.698	100 to 500
Souder, Hidnert (1926)	33.9	21.61		−183 to 0

Callendar (1913 B) $10^8\,\alpha \text{ (linear)} = 78.0 - \dfrac{8650}{t + 175}$ 0 to 300° C.

Harlow (1929) $10^8\,\alpha \text{ (linear)} = 66.3 - \dfrac{3879}{t + 103}$ 0 to 300° C

Temp. ° C.	$10^8\,\alpha$ (linear) °C.$^{-1}$										
	Chappuis	Henning[1]	Randall[1]	Donaldson	Callendar[2]	Scheel[3]	Souder Hidnert[1]	Wheeler Summary	Sosman Summary	Harlow Summary	Our Values
	1903	1907	1910	1912	1913	1914 1921	1926	1914	1927	1929	1940
−150						1.4	1.5	0.0	− 3.3		2.4
−125						8.2	6.9	7.0			10.1
−100						14.7	12.3	14.3	+13.3		17.0
− 75						20.7	17.7	21.2			23.3
− 50						26.3	23.1	27.0	25.0		28.9
− 25					22.3	31.5	28.5	31.2			33.9
0	38.5			38.0	29.0	36.2	33.9		38.3	28.6	38.2
+ 25	41.3			40.8	34.8	40.5		39.4		36.0	41.9
50	44.2				39.8	44.4		42.8	43.3	40.9	45.1
75	47.1		41.0		43.8	47.9		46.1		44.5	47.9
100			43.5		47.0	50.9	43.6	48.8	48.3	47.2	50.2
150			47.6		51.4	54.9		51.5	51.7	51.0	53.7
200			50.5		54.9	58.3	48.8	52.5	53.3	53.5	55.9
250		52.8	52.5		57.6	60.9		54.0		55.3	57.2
300			53.9		59.8	62.7	52.0	55.3	55.7	56.7	57.9
350			54.9			63.6		55.7			57.9
400			55.6			63.6	54.2	55.5	56.7		57.6
450			56.0			62.8		55.8			57.0
500		53.4	56.2			61.2	51.4	55.8	56.7		

[1] Corrected from 16-to-*t* or 20-to-*t* to 0-to-*t* by use of α (linear) $\times 10^8 = 38.0$ from 0-to-16 or 0-to-20.

[2] Values −25 to +100 from (1913A) equation; 150 to 300 from (1913B) equation.

[3] Values −150 to +100 from (1914) equation; 150 to 500 from (1921) equation. The values in this column agree with the Wärmetabellen summary.

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L. Holborn and F. Henning, Ann. der Physik, [4] **10,** 446–448 (1903); F. Henning, ibid., [4] **22,** 631–639 (1907).

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K. Scheel, Verh. Deutsch. Phys. Ges., **5,** 119–123 (1903); Wiss. Abh. Phys. Tech. Reich., **4,** 35–60 (1904); Verh. Deutsch. Phys. Ges., **9,** 3–23, 718–721 (1907); K. Scheel and W. Heuse, ibid., **16,** 1–3 (1914); K. Scheel, Zeit. f. Physik, **5,** 167–172 (1921). See also L. Holborn, K. Scheel, and F. Henning, *Wärmetabellen,* F. Vieweg und Sohn, Braunschweig, 1919.

W. Souder and P. Hidnert, Scien. Papers Bureau of Standards, **21,** 1–23 (1926).

N. E. Wheeler, Trans. Royal Soc. Canada, **III 8,** 139–156 (1914).

R. B. Sosman, *The Properties of Silica,* The Chemical Catalog Co. Inc., New York, 1927.

F. J. Harlow, Proc. Phys. Soc. London, **26,** 85–94 (1913–14); Phil. Mag., [7] **7,** 674–685 (1929).

Eq. (B) given in Table I was obtained from Eq. (A) by approximation. The values of $(V - V_0)/V_0$ computed from Eqs. (A) and (B) agree to 0.01×10^{-6} from 0° to 450° C., the difference increasing below 0° to 0.15×10^{-6} at − 175° C. The agreement is far better than the accuracy of the data.

In Table II the residuals of Table I are added algebraically in each 50° temperature range for the low temperature runs and at each temperature for the high temperature series. The results indicate that the equation follows the trends of the measurements quite well to − 175° C. which is below the temperature of minimum length, − 84.6° C. The root-mean-square deviations $(\Sigma v^2/n)^{1/2}$ of $(l - l_0)/l_0$ from the four-constant equation, Eq. (A), are given in Table I and the average of the algebraic average of the residuals in each temperature range in Table II. The probable error of a single determination computed from the residuals given in Table I is 0.562×10^{-6} in $(l - l_0)/l_0$ (80 points, 10 series, 4 constant equation); the reproducibility of a single reading was about one twentieth of a band width or 0.7×10^{-6} in $(l - l_0)/l_0$.

In Table III the results of the present investigation are compared with the values given by other workers, and the summaries of Wheeler, Sosman, and Harlow. The agreement with Sosman's selected values is fair.

(*b*) *Compressibility of Vitreous Silica*

In Table IV are given the results of the measurements of the number of grams of mercury forced out of the bulbs at several temperatures when the external pressure p_e was increased from about $p_b - 700$ mm. to about p_b. The internal pressure $p(= p_B + p_h)$ remaining constant at about 1.7 atm. to within ± 0.3 mm. Hg in any one experiment, but varying by as much as 1 mm. Hg (due to variation in p_B) from experiment to experiment at one temperature, and by as much as 25 mm. from 25° to 300° due to variation in p_h. No correction was made for these effects which affect the measurements by an amount less than the error of weighing. The number of grams of mercury that ran out, or the corresponding change in the volume of the bulb, divided by the final minus the initial value of p_e gives the effect produced by a unit change in $p_b - p_e$, p_b remaining constant.

Each of the values of C (gm. Hg/standard mm. Hg) in Table IV is the mean of four, the average deviation being about 1%. The quantities C were converted to the corresponding dilations of the bulb γ in ml./mm. Hg by division by the density of mercury at t. The least square equations for C and γ expressed as linear functions of temperature are given in the heading of Table IV and the deviations of the calculation from the observed values in the body of the table.

In Table V the dilations given in Table IV are used to compute the mean coefficient of compressibility of vitreous silica at low pressure. In the computation we assumed: (1) each bulb behaved as though it were a thin spherical shell plus a thin cylindrical shell with unconstrained ends; (2) the bulbs were of uniform thickness so that the dimensions of the parts could be computed from the mass, internal volume, and external diameter. The error introduced by the first assumption as regards the effect of the interaction of the hemispherical caps and the cylinder at the planes of jointure can be estimated[2] and is less than the errors of the data.

TABLE IV

DILATION OF THE VITREOUS SILICA BULBS CAUSED BY A DIFFERENCE BETWEEN INTERNAL AND EXTERNAL PRESSURE

C_b = grams of mercury forced out of the bulb per standard mm. Hg decrease in $p_b - p_e$.
$\gamma_b = C_b/\delta_{Hg}$ = ml. increase in volume of bulb per standard mm. Hg increase in $p_b - p_e$.

Equations: Red Bulb: $10^3 C_b = 0.9700 - 3.43 \times 10^{-4} t$ (A)
$10^3 \gamma_b = 0.0714 - 1.3 \times 10^{-5} t$ (B)
Green Bulb: $10^3 C_b = 1.1172 - 3.61 \times 10^{-4} t$ (C)
$10^3 \gamma_b = 0.0822 - 1.3 \times 10^{-5} t$ (D)

t ° C. (Int.)	δ_{Hg} gm./ml.	Red Bulb				Green Bulb			
		$C_b \times 10^3$		$\gamma_b \times 10^3$		$C_b \times 10^3$		$\gamma_b \times 10^3$	
		Obsd.	Obsd.-Eq. A	Obsd.	Obsd.-Eq. B	Obsd.	Obsd.-Eq. C	Obsd.	Obsd.-Eq. D
25	13.5340	0.9648	+0.0034	0.07129	+0.00021	1.1108	+0.0026	0.08207	+0.00019
100	13.3518	.9349	− .0008	.07002	− .00008	1.0801	− .0010	.08090	.00000
200	13.1127	.8935	− .0079	.06814	− .00066	1.0397	− .0053	.07929	− .00031
300	12.8747	.8723	+ .0052	.06775	+ .00025	1.0124	+ .0035	.07863	+ .00033

Note: Each tabulated value of C_b is the average of four measurements with an average deviation of 1%.

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[2] E. Meissner, Schweizerische Bauzeitung, **86,** 1–5 (1925).

TABLE V

CALCULATION OF THE MEAN COEFFICIENT OF COMPRESSIBILITY OF VITREOUS SILICA

$\gamma_b = (A\beta + B/\mu)\,(p_i - p_e)$.

p_i was constant; p_e was varied; γ_b is given in Table IV.

$\beta = -(1/V_t)\,(\Delta V/\Delta p)_t$ or $-(1/V_0)\,(\Delta V/\Delta p)_t$; same value for vitreous silica to number of significant figures given (V_t is volume at t° C. and 1 atm.; V_0 at 0° C. and 1 atm.).

μ = rigidity

$$A = \left(\frac{V_eV_i}{V_e - V_i}\right)_{\text{sphere}} + \left(\frac{V_eV_i}{V_e - V_i}\right)_{\text{cylinder}};\quad B = \tfrac{3}{4}\left(\frac{V_eV_i}{V_e - V_i}\right)_{\text{sphere}} + \left(\frac{V_eV_i}{V_e - V_i}\right)_{\text{cylinder}}$$

e denotes external; i denotes internal; b denotes the bulb.

		Red Bulb		Green Bulb	
		δ_b = 2.208 gm. ml.$^{-1}$			
Mass (measured)		270.0 gm.		249.0 gm.	
V_e		1108.6 ml.		1128.2 ml.	
V_i (measured)[a]		986.3		1015.4	
r_e (measured)		4.225 cm.		4.245 cm.	
r_i		4.014		4.053	
length of cylinder		14.135		14.269	
thickness		0.211		0.192	
		Sphere	Cylinder	Sphere	Cylinder
V_e		315.9 ml.	792.7 ml.	320.4 ml.	807.8 ml.
V_i		270.9	715.5	278.9	736.4
A		9249 $(1 + a_bt_b)$ ml.		10485 $(1 + a_bt_b)$ ml.	
B		8773 $(1 + a_bt_b)$		9946 $(1 + a_bt_b)$	
Temp.	$\mu \times 10^{-5}$[b]	$\gamma_b \times 760$	$\beta \times 10^6$	$\gamma_b \times 760$	$\beta \times 10^6$
°C. (Int.)	atm.	ml./atm.	atm.$^{-1}$	ml./atm.	atm.$^{-1}$
25	2.964	0.05418	2.66	0.06237	2.75
100	2.985	.05322	2.58	.06148	2.69
200	3.013	.05179	2.45	.06026	2.60
300	3.040	.05149	2.44	.05976	2.58

[a] Without capillary ends.

[b] F. Horton, Phil. Trans. Royal Soc. London, **204A**, 407–431 (1905).

TABLE VI

COMPARISON OF THE MEAN COEFFICIENT OF COMPRESSIBILITY OF VITREOUS SILICA WITH THE VALUES OF OTHER INVESTIGATORS

$$\text{Equations: } \beta \times 10^6\ (\text{atm.}^{-1}) = 2.70 - 6 \times 10^{-4}t \qquad \text{(A)}$$

$$\beta \times 10^9\ (\text{mm. Hg}^{-1}) = 3.55 - 8 \times 10^{-4}t \qquad \text{(B)}$$

Temp. ° C.	$\beta \times 10^6$ atm.$^{-1}$					
	Red	Green	Mean	Eq. A.	Birch, Dow[1]	Others[2]
0				2.70	2.57	
25	2.66	2.75	2.70	2.68		2.68–2.72
100	2.58	2.69	2.64	2.64	2.60	
200	2.45	2.60	2.52	2.58	2.51	
300	2.44	2.58	2.51	2.52	2.45	
400				2.46	2.48	

[1] F. Birch and R. B. Dow, Bull. Geol. Soc. Am., **47**, 1235–1255 (1936).

[2] R. B. Sosman, *International Critical Tables*, Vol. IV, p. 21 (1928), selects 2.72; L. H. Adams and R. E. Gibson, J. Wash. Acad. Sci., **21**, 381–390 (1931), obtain 2.72; F. Birch and R. R. Law, Bull. Geol. Soc. Am., **46**, 1219–1249 (1935), obtain 2.68, F. Birch, J. Applied Phys., **8**, 129–133 (1937), computes 2.69. All are for temperatures in the neighborhood of 25° C. and for low pressures.

The error introduced by the assumption of uniform thickness and precise shape is unknown. Measurement of the thickness of a broken bulb showed that there was a fair variation. The rigidity term $(B/\mu)\ (p_i - p_e)$ accounts for about one half of ΔV_b so that our computation of β are quite dependent on the measurements of Horton, who used vitreous silica fibers.

In Table VI the values of the mean coefficient of compressibility of vitreous silica derived in Table V are given together with the results of other investigators and the equations we used to express β as a function of temperature. Our two bulbs gave values about 5% apart due no doubt to the assumption of uniform thickness. Our average values are in good agreement with the work of other investigators at 25°; and are within about 2% of the measurements of Birch and Dow at and above 100° C.

(c) *Thermal Dilation of Mercury*

The corrected mass M_{wt_r} of mercury in the weighing bottles was computed by Eqs. (7) to (9) from the measured mass M_{wt_b} and the following data.

From the indications of the thermocouple for each thermostat temperature we determined from plots of temperature against distance: (1) the average temperature t_β from -38 to $+18$ (Fig. 1); (2) the average temperature t_γ from -28 to $+14$; and the three average temperatures t_i $(i = 1, 2, 3)$ into which the dead space from -20 to $+20$ was divided.

Then:

$$p_b(\text{atm.}) = p_B(\text{atm.}) + \frac{560\ [1 + \alpha_b(\text{linear})t_\beta]}{760\ (1 + \alpha_{Hg}\ t_\beta)}$$

$$p_b - p_e(\text{mm. Hg}) = 37 - \frac{420\ [\alpha_s(\text{linear}) - \alpha_b(\text{linear})]\ t_\gamma}{1 + 27\ \alpha_{Hg}}$$

where the subscript s denotes steel.

The true and the mean coefficients of thermal dilation and the mean coefficient of linear thermal expansion of vitreous silica are given in Tables XV to XVII. The mean coefficient of cubical compressibility of vitreous silica is given in Table VI, and the dilation of the bulbs caused by a difference between internal and external pressure in Table IV. The mean coefficient of linear thermal expansion of steel, and the true and the mean coefficients of thermal dilation of mercury were taken from International Critical Tables. The coefficient of cubical compressibility of mercury was taken to be

$$\beta_{Hg} \times 10^{-6}(\text{atm.}^{-1}) = 3.89 + 5.5 \times 10^{-3}t$$

and the standard density of mercury, 13.59546 gm./ml.

The bulb was considered to extend to -20 (Fig. 1); the section of capillary from -20 to $+20$ in the region of large thermal gradient was divided into the three parts $i = 1, 2, 3$; and the final length from $+20$ to the tip was $i = m$. The point 0 was the top of the thermostat cover. For the highest temperature run in each thermostat, the correction for the length of capillary -20 to $+20$ was checked by computing the correction for the section when divided into 16 parts each 2.5 cm. long, the proper volume and temperature being associated with each length. The maximum error in the correction obtained by division into three parts is less than 5×10^{-4} gm. mercury.

In Table VII are given the values of

$$\Delta M_{wt} = (M_{wt_2} - M_{wt_1})\frac{1000}{V_{b0}}$$

the corrected number of grams of mercury (reduced to 1000 ml. basis) that ran out of the bulb when the temperature was increased from t_1 to t_2, the temperatures being given in Column II and the run numbers in Column I. The entries are arranged by increasing temperatures. These values were treated by the method of least squares[3] to obtain the most probable values of m, that is $M_{wt} - M_{w0}$, Red and Green being treated separately. Under the heading obsd.-calcd. are given the deviations of the values of ΔM_{wt} for each bulb from those computed from the corresponding m's. The root-mean-square deviations are 86.01×10^{-4} gm. Hg (39 points) for Red and 114.72×10^{-4} gm. Hg (39 points) for Green. The root-mean-square deviation of ΔM_{wt} for Red and Green taken together from the values computed from the average values of m given in Table VII is 270.49×10^{-4} gm. Hg (78 points).

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[3] A. Pérard, Trav. et Mém. Bureau Int., **16**, 77 pp. (1917).

TABLE VII

CALCULATION OF MOST PROBABLE VALUES OF m

Deviations are from the values computed from the most probable values of m (one set for Red and one for Green) tabulated at the bottom.

m = most probable mass of mercury (gms.) flowing out of Red (or Green) bulb when heated from 0° to t° C.

α_b (Red)/α_b (Green) = ratio of mean coefficient of thermal dilation of Red to that of Green bulb which would explain the difference in the preceding column.

Run Nos.	Temps.	Red Bulb		Green Bulb		Green-Red
		ΔM_{wt}	Obsd.-calcd.	ΔM_{wt}	Obsd.-calcd.	$\Delta(\Delta M_{wt})$
	°C. Int.	gms. Hg/1000 ml.	gms. Hg × 10^4	gms. Hg/1000 ml.	gms. Hg × 10^4	gm. Hg × 10^4
15–16	0–25	61.0183	− 84	61.0147	−207	− 36
21–22	0–25	61.0206	− 61	61.0294	− 60	+ 88
14–15	0–50	121.6015	− 11	121.5886	−103	− 129
5–6	0–75	181.7779	+111	181.7877	+132	+ 98
6–7	0–100	241.5963	+ 71	241.6075	+ 79	+ 112
20–21	0–152.315	365.9343	− 26	365.9722	+160	+ 379
2–3	25–50	60.5723	− 36	60.5645	+ 10	− 78
16–17	25–50	60.5928	+169	60.5689	+ 54	− 239
9–10	25–75	120.7213	−188	120.7247	−144	+ 34
1–2	25–100	180.5710	+ 85	180.5567	− 75	− 143
10–11	25–152.315	304.8929	−173	304.9097	−111	+ 168
17–18	50–75	60.1737	+ 95	60.1747	− 9	+ 10
3–4	50–100	119.9934	+ 68	119.9992	− 15	+ 58
13–14	50–152.315	244.3299	− 44	244.3556	− 17	+ 257
4–5	75–100	59.8170	− 54	59.8169	− 82	− 1
18–19	75–100	59.8183	− 41	59.8222	− 29	+ 39
8–9	75–152.315	184.1848	+147	184.2035	+218	+ 187
11–12	75–152.315	184.1731	+ 30	184.1754	− 63	+ 23
12–13	75–152.315	184.1635	− 66	184.1751	− 66	+ 116
7–8	100–152.315	124.3550	+ 73	124.3328	−238	− 222
19–20	100–152.315	124.3534	+ 57	124.3679	+113	+ 145
24–25	150–152.315	5.4873	+ 21	5.4893	+ 23	+ 20
25–26	150–152.315	5.4796	− 56	5.4887	+ 17	+ 91
31–32	150–152.315	5.4892	+ 40	5.4928	+ 58	+ 36
32–33	150–152.315	5.4775	− 77	5.4663	−207	− 112
38–39	150–152.315	5.4977	+125	5.4906	+ 36	− 71
39–40	150–152.315	5.4797	− 55	5.4941	+ 71	+ 144
33–34	152.315–200	112.7325	+ 47	112.7498	+229	+ 173
40–41	152.315–200	112.7295	+ 17	112.7334	+ 65	+ 39
37–38	152.315–250	230.6996	− 12	230.7122	+ 25	+ 126
23–24	152.315–300	348.8397	− 26	348.8620	−139	+ 223
26–27	152.315–300	348.8470	+ 47	348.8812	+ 53	+ 342
30–31	152.315–350	467.7777	− 71	467.9224	−232	+1447
28–29	200–250	117.9743	+ 13	117.9902	+ 74	+ 159
34–35	200–300	236.1307	+162	236.1560	+ 70	+ 253
29–30	200–350	355.0458	−112	355.2338	+151	+1880
27–28	250–300	118.1350	− 65	118.1655	− 7	+ 305
36–37	250–350	237.0908	+ 68	237.2466	+107	+1558
35–36	300–350	118.9541	+116	119.0673	− 24	+1132
Root-mean-square deviation			86.01		114.72	513.32[a]
Algebraic average						+ 220.79[a]

Temps. °C. Int.	Most probable values of m (gms. Hg/1000 ml.)				
	Red Bulb	Green Bulb	Average	(Green-Red) × 10^4	a_b(Red)/a_b(Green)
0–25	61.0267	61.0354	61.0310	+ 87	1.0204
0–50	121.6026	121.5989	121.6008	− 37	0.9959
0–75	181.7668	181.7745	181.7706	+ 77	1.0053
0–100	241.5892	241.5996	241.5944	+ 104	1.0052
0–150	360.4517	360.4692	360.4604	+ 175	1.0055
0–152.315	365.9369	365.9562	365.9466	+ 193	1.0059
0–200	478.6647	478.6831	478.6739	+ 184	1.0042
0–250	596.6377	596.6659	596.6518	+ 282	1.0051
0–300	714.7792	714.8321	714.8056	+ 529	1.0079
0–350	833.7217	833.9018	833.8118	+1801	1.0232
Root-mean-square deviation				610.77[b]	
Algebraic average				+ 339.50[b]	

[a] If the four points which involve 350° are omitted 513.32 becomes 163.83 and +220.79 becomes + 74.11.

[b] If the point at 350° is omitted 610.77 becomes 232.56 and +339.50 becomes +177.11.

TABLE VIII

Mean Coefficient of Thermal Dilation of Mercury

$$\alpha_b = 3\alpha_b \text{ (linear) } [1 + \alpha_b \text{ (linear) } t] \quad [\alpha_b \text{ (linear) from Eq. (A), Table I}].$$

$$\alpha_{Hg} \text{ (apparent)} = \frac{m}{t(M_{b0} - m)}. \qquad [M_{b0} = 13595.46]$$

$$\alpha_{Hg} \text{ (obsd.)} = \alpha_{Hg} \text{ (apparent)} + \frac{M_{b0}\,\alpha_b}{M_{b0} - m}.$$

$$\alpha_{Hg} \times 10^8 \text{ (calcd.)} = 18144.01 + 70.16 \times 10^{-2}t + 28.625 \times 10^{-4}t^2 + 2.617 \times 10^{-6}t^3.$$

$$m \text{ (calcd.)} = \frac{M_{b0}\,t(\alpha_{Hg} - \alpha_b)}{1 + \alpha_{Hg}t}.$$

t	m (0 to t)	$\alpha_b \times 10^8$	α_{Hg} (app.) $\times 10^8$	$\alpha_{Hg} \times 10^8$ (obs.)	$\alpha_{Hg} \times 10^8$ (calcd.)	(Obsd. − calcd.) $\times 10^8$	m (calcd.)	(Obsd. − calcd.) $\times 10^4$
°C. Int.	gm. Hg/1000 ml.	°C.$^{-1}$	°C.$^{-1}$	°C.$^{-1}$	°C.$^{-1}$	°C.$^{-1}$	gm. Hg/1000 ml.	gm. Hg/1000 ml.
25	61.0310	125.78	18037.259	18163.606	18163.380	+0.226	61.0302	+ 8
50	121.6008	135.44	18049.884	18186.547	18186.573	−0.026	121.6010	− 2
75	181.7706	143.64	18068.168	18213.755	18213.836	−0.081	181.7714	− 8
100	241.5944	150.54	18091.720	18244.984	18245.412	−0.428	241.6000	− 56
150	360.4604	160.98	18156.928	18322.292	18322.489	−0.197	360.4642	− 38
200	478.6739	167.78	18246.615	18420.518	18419.766	+0.752	478.6549	+190
250	596.6518	171.75	18360.200	18539.834	18539.207	+0.627	596.6323	+195
300	714.8056	173.58	18498.170	18681.383	18682.774	−1.391	714.8565	−509
350	833.8118	173.82	18667.804	18852.981	18852.430	+0.551	833.7887	+231
Root-mean-square deviation*						0.62159		208.51

* Root-mean-square deviations of ΔM_{wt} of Table VII from calculated values are: Red, 331.59 $\times 10^{-4}$ (39 points); Green, 388.64 $\times 10^{-4}$ (39 points); Red and Green, 361.24 $\times 10^{-4}$ (78 points).

It will be noticed (Table VII) that ΔM_{wt} and m are systematically larger for Green than for Red bulb. The root-mean-square deviations are: 513.32 $\times 10^{-4}$ gm. Hg (39 points) for ΔM_{wt} or 163.83 $\times 10^{-4}$ gm. Hg (35 points) if the 350° points are excluded; 610.77 $\times 10^{-4}$ gm. Hg (10 points) for m or 232.56 $\times 10^{-4}$ gm. Hg (9 points) if the 350° point is excluded. The average of the algebraic sum of $\Delta(\Delta M_{wt})$, Green minus Red, is + 220.79 $\times 10^{-4}$ gm. Hg (+ 74.11 $\times 10^{-4}$ if the 350° points are excluded); and that for Δm, Green minus Red, is + 339.50 $\times 10^{-4}$ gm. Hg (+ 177.11 $\times 10^{-4}$ if the 350° point is excluded). From Eq. (10)

$$t\Delta\alpha_{Hg} = \Delta m \frac{1 + \alpha_{Hg}t}{M_{b0} - m}, \tag{13}$$

$$t\Delta\alpha_b = -\Delta m \frac{1 + \alpha_{Hg}t}{M_{b0}}. \tag{14}$$

The difference between m for Red and for Green bulb can be explained by a difference $\Delta\alpha_{Hg} = 1 \times 10^{-8}$ °C.$^{-1}$ (the 350° point is excluded) where $\alpha_{Hg} \cong 18000 \times 10^{-8}$ °C.$^{-1}$ or a difference $\Delta\alpha_b = -1 \times 10^{-8}$ °C.$^{-1}$ where $\alpha_b \cong 160 \times 10^{-8}$ °C.$^{-1}$ A third cause of this difference would be the presence of a small amount of air in the Green bulb; we believe this to be very improbable. Calculation shows that the presence of a constant amount of air in the bulb would not account for the variation of the difference with temperature.

In the present calculations we shall consider the data taken with Red bulb and Green bulb to be equally accurate and use the mean m. For our gas thermometer calculations we shall take α_b (Red)/α_b (Green) = 1.005.

In Table VIII are given the computations of the mean coefficient of thermal dilation of mercury from the mean values of m of Table VII, the constants of a four-constant equation for α_{Hg} determined by the method of least squares, and the deviations of the calculated from the observed values of α_{Hg} and m. The root-mean-square deviations of the 9 points from the four-constant equation are: 0.621 59 $\times 10^{-8}$ °C.$^{-1}$ for α_{Hg} and 208.51 $\times 10^{-4}$ gm. Hg for m; the corresponding probable errors of a single determination are 0.562 $\times 10^{-8}$ °C.$^{-1}$ for α_{Hg} and 188.7 $\times 10^{-4}$ gm. Hg for m. The root-mean-square deviations of ΔM_{wt} observed (Table VII) from the values computed from the four-constant equation are: 331.59 $\times 10^{-4}$ gm. Hg (39 points) for Red bulb; 388.64 $\times 10^{-4}$ gm. Hg (39 points) for Green bulb; 361.24 $\times 10^{-4}$ gm. Hg (78 points) for Red and Green bulbs. This last value corresponds to a

TABLE IX

Comparison of our Values of the Mean Coefficient of Thermal Dilation of Mercury with the Results of other Investigators

$\alpha_{Hg} \times 10^8 = a + bt + ct^2 + dt^3$

Author	Date	a	$b \times 10^4$	$c \times 10^6$	$d \times 10^8$	Range	Bulb
P. T. R. (A)	1895–1919	18182	7800			0–100	16^{III} 59^{III}
P. T. R. (B)	1895–1919	18181	3470	3930	− 20	100–300	59^{III}
Chappuis	1907	18169.041	−2951.266	11456.2		0–100	verre dur
Chappuis	1917	18163.674	+8469.42			0–100	absolute method
Callendar, Moss	1912	18055.53	12444	2539		0–300	absolute method
Sears	1914	18145.6	9205	660.8	+673.20	0–300	vitreous silica
Harlow	1929	18153.8	7548	1533	536	0–300	vitreous silica
This investigation	1940	18144.01	7016	2862.5	261.7	0–350	vitreous silica

	$\alpha_{Hg} \times 10^8$ °C.$^{-1}$	$\Delta\alpha_{Hg} \times 10^8$, other author—our equation									
Temp., °C. Int.	This investigation	P.T.R. (A)	P.T.R. (B)	Chappuis	Chappuis	Callendar, Moss	James*	Harlow*	Sears	Harlow*	Harlow
	1940	1895–1919	1895–1919	1907	1917	1912	1914	1914	1914	1929	1929
25	18163	+39		+6	+22	−75			+ 6		+11
30	18168							0		+ 7	
50	18187	+34		−4	+19	−63		+1	+ 7	+ 5	+ 9
75	18214	+26		−3	+13	−51		−1	+ 7	+ 2	+ 7
100	18245	+15	+10	+9	+ 3	−40	−4	−1	+ 6	+ 2	+ 5
140	18306							−1		− 1	
150	18322		− 1			−23			− 1		− 2
184	18386							+1		− 4	
200	18420		−14			−14		−1	−10	− 8	−11
250	18539		−29			−14		−2	−17	−12	−17
300	18683		−50			−26		−5	−20	−15	−20

* Original data; all other entries are computed from the equations given.

References:

P.T.R.; M. Thiesen, K. Scheel, and L. Sell, Wiss. Abh. Phys. Tech. Reich., **2,** 75–184 (1895); Zeit. f. Instr., **16,** 49–58 (1896); K. Scheel and W. Heuse, Verh. Deut. Phys. Ges., **14,** 139–144 (1912); F. Hoffmann and W. Meissner, Zeit. f. Instr., **39,** 212–224 (1919); L. Holborn, K. Scheel, and F. Henning, *Wärmetabellen,* F. Vieweg und Sohn, Braunschweig, 1919.

P. Chappuis, Trav. et Mém. Bureau Int., **13,** 31 pp. (1907); ibid., **16,** 31 pp. (1917).

H. L. Callendar and H. Moss, Phil. Trans., **211A,** 1–32 (1912); Proc. Royal Soc. London, **84A,** 595–597 (1910–11).

C. B. James, Trans. Royal Soc. Canada, **III8,** 51–58 (1914).

F. J. Harlow, Proc. Phys. Soc. London, **26,** 85–96 (1914); Phil. Mag., [7] **7,** 674–685 (1929).

Sears, Proc. Phys. Soc. London, **26,** 95 (1914).

probable error of 250.2 × 10^{-4} gm. Hg (78 points) or approximately 0.002 ml. in the volume of mercury run out of a one-liter bulb.

In Table IX the mean coefficients of thermal dilation of mercury computed from our equation are compared with the values of other investigators. The accord of our equation for α_{Hg} with the measurements of Harlow (1914) is astonishingly good, the root-mean-square deviation being 1.97 × 10^{-8} °C.$^{-1}$ (9 points). In 1929 Harlow recomputed his measurements using the apparent coefficients of dilation determined in 1914 but new values of α_b for vitreous silica obtained from a critical survey of all of the available data (see Table III). Our equation does not agree so well with his 1929 values, the root-mean-square deviation being 7.69 × 10^{-8} °C.$^{-1}$ (9 points). It is possible that the values of α_b used by Harlow in 1914 which were determined by Callendar (see Table III) with a sample made at the same time that the bulbs were manufactured more nearly represented the thermal dilation of Harlow's bulbs than the values he selected in 1929.

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6. Summary

The apparent mean coefficient of thermal dilation of mercury in each of two one-liter vitreous silica bulbs has been determined for the tempera-

TABLE X

MEAN COEFFICIENT OF THERMAL DILATION OF MERCURY FROM 0° TO t° C.

$$\alpha^\circ \text{ C.}^{-1} \text{ (Int.)} \times 10^8 = \frac{V_t - V_0}{tV_0}.$$

$$= 18144.01 + 70.16 \times 10^{-2}t + 28.625 \times 10^{-4}t^2 + 2.617 \times 10^{-6}t^3. \quad (0^\circ < t^\circ \text{ C. (Int.)} < 350^\circ)$$

°C. (Int.)	0	1	2	3	4	5	6	7	8	9
	α° C.$^{-1}$ (Int.) × 10^8									
0	18 144.01	18 144.71	18 145.42	18 146.14	18 146.86	18 147.59	18 148.32	18 149.06	18 149.81	18 150.56
10	151.31	152.08	$152.8\bar{5}$	153.62	154.40	155.19	155.98	156.78	157.58	158.39
20	159.21	160.03	160.86	161.69	162.53	163.38	164.23	165.09	165.96	166.83
30	167.70	168.59	169.48	170.37	171.28	172.18	173.10	174.02	$174.9\bar{5}$	175.88
40	176.82	177.77	178.72	179.68	$180.6\bar{5}$	181.62	182.60	183.58	184.57	185.57
50	186.57	187.58	188.60	189.63	190.66	191.69	192.74	193.79	194.84	195.91
60	196.98	198.05	199.14	200.23	201.32	202.43	203.54	204.65	205.78	206.91
70	$208.0\bar{5}$	209.19	210.34	$211.5\bar{0}$	212.66	213.84	215.01	216.20	217.39	218.59
80	219.80	221.01	222.23	223.46	224.69	225.93	227.18	228.44	229.70	230.97
90	$232.2\bar{5}$	233.53	234.82	236.12	237.43	238.74	240.06	241.39	242.72	244.06
100	245.41									

°C. (Int.)	00	10	20	30	40	50	60	70	80	90
	α° C.$^{-1}$ (Int.) × 10^8									
100	18 245.41	18 259.31	18 273.94	18 289.34	18 305.52	18 322.49	18 340.27	18 358.87	18 378.31	18 398.60
200	419.77	441.82	464.77	$488.6\bar{5}$	513.45	539.21	565.93	593.63	622.33	652.04
300	682.77	714.56	747.40	781.31	816.32	852.43				

ture range 0° to 350° C. Thirty-nine measurements were made with each bulb.

The thermal expansion of a ring of vitreous silica prepared from one of the bulbs and annealed in the same manner as the bulb was measured at 88 temperatures from − 200° to + 450° C. The results may be represented by the equations:

$$\frac{l - l_0}{l_0} \times 10^6 = \frac{t^2 + 157.361t}{0.00126792t^2 + 0.88121t + 412.109}, \quad -175^\circ < t^\circ\text{C.} < +450^\circ$$

$$\frac{V - V_0}{V_0} \times 10^6 = \frac{t^2 + 157.281t}{0.0004225t^2 + 0.29362t + 137.32}, \quad -175^\circ < t^\circ\text{C.} < +450^\circ$$

where t is on the Centigrade thermodynamic temperature scale when below 0° C. and on the International scale when above 0°, l_0 [V_0] is the length [volume] at 0° C., and l [V] the length [volume] at t°. The probable error of a single determination measured by the deviations of the observed values from those computed from this equation is 0.56×10^{-6} in $(l - l_0)/l_0$ (80 points, 10 series). The temperature of minimum length of the sample was − 84.6° C. The values of the mean coefficient of linear thermal expansion of vitreous silica computed from the equation are in fair agreement with the values selected by Sosman.

From the dilation of the bulbs caused by a difference between internal and external pressure at several temperatures and Horton's values of the rigidity we computed the mean coefficient of compressibility of vitreous silica at low pressures as a function of temperature:

$$\beta \times 10^6 \text{ (atm.}^{-1}) = 2.70 - 6 \times 10^{-4}t, \quad 0^\circ < t^\circ \text{ C.} < 300^\circ$$

where t is in degrees Centigrade. The values computed from the equation are in good agreement with those obtained by the compressibility methods. The values of β for the two bulbs differed about 5%.

The apparent mean thermal dilations of mercury determined in the two bulbs differed systematically by an amount that could be interpreted as a variation in the mean coefficient of thermal dilation of mercury of 1×10^{-8} °C.$^{-1}$ (about 1 part in 18000) or a variation in the mean coefficient of thermal dilation of the vitreous silica of the bulbs of 1×10^{-8} °C.$^{-1}$ (about 1 part in 160). In terms of volume this systematic difference between the results in the one bulb and in the other is on the average 0.002 ml. in 1000 ml. or 2 parts in $10.^6$

We considered the results obtained by use of the two bulbs equally accurate for the present purpose. The equation obtained for the thermal dilation of mercury is

$$\frac{V-V_0}{V_0} \times 10^8 = \alpha_{Hg}t \times 10^8 = 18144.01t + 70.16 \times 10^{-2}t^2 + 28.625 \times 10^{-4}t^3 + 2.617 \times 10^{-6}t^4, \quad 0^\circ < t^\circ \text{ C.} < 350^\circ$$

where t is on the International temperature scale. The probable error of a single determination of α_{Hg} is 0.56×10^{-8} °C.$^{-1}$ (9 points). The above equation agrees well with the 1914 measurements of Harlow, the probable error of a single determination of α_{Hg} being 1.78×10^{-8} °C.$^{-1}$ (9 points).

Values of the following quantities as functions of temperature are tabulated for mercury from 0° to 350° C.: the true and the mean coefficients of thermal dilation, the density and the specific volume, and the ratio of the density at $t°$ to that at 0° C. Tables for the following properties of vitreous silica are given from − 150° to + 450° C.: the true and the mean coefficients of linear thermal expansion and of thermal dilation.

TABLE XI

TRUE COEFFICIENT OF THERMAL DILATION OF MERCURY AT $t°$ REFERRED TO 0° C.

$$\alpha' = \frac{1}{V_0}\frac{dV}{dt} = \frac{d\,(\alpha t)}{dt}.$$

°C. (Int.)	00	10	20	30	40	50	60	70	80	90
	α'° C.$^{-1}$ (Int.) × 10^8									
0	18 144.01	18 158.91	18 175.59	18 194.12	18 214.5$\bar{5}$	18 236.9$\bar{5}$	18 261.38	18 287.90	18 316.59	18 347.49
100	18 380.67	18 416.20	18 454.14	18 494.55	18 537.5$\bar{0}$	18 583.04	18 631.24	18 682.16	18 735.87	18 792.43
200	18 851.89	18 914.33	18 979.81	19 048.39	19 120.13	19 195.09	19 273.34	19 354.94	19 439.96	19 528.45
300	19 620.48	19 716.11	19 815.41	19 918.43	20 025.2$\bar{5}$	20 135.91				

TABLE XII

RATIO OF THE DENSITY OF MERCURY AT $t°$ TO THE DENSITY AT 0° C.

$$\frac{\delta_t}{\delta_0} = \frac{V_0}{V_t} = \frac{1}{1 + \alpha t}$$

°C. (Int.)	0	1	2	3	4	5	6	7	8	9
	$\delta_t/\delta_0 = V_0/V_t = (1 + \alpha t)^{-1}$									
0	1.0000 0000	0.9998 1859	0.9996 3722	0.9994 5591	0.9992 7465	0.9990 9344	0.9989 1229	0.9987 3118	0.9985 5012	0.9983 6911
10	0.9981 8816	80 072$\bar{5}$	78 2639	76 4559	74 6483	72 8412	71 0346	69 228$\bar{5}$	67 4228	65 6177
20	63 8130	62 0088	60 2051	58 4019	56 5991	54 7968	52 995$\bar{0}$	51 1936	49 3927	47 5923
30	45 7923	43 9928	42 1938	40 3952	38 5970	36 7993	35 0021	33 2053	31 4089	29 6130
40	27 8175	26 022$\bar{5}$	24 2279	22 4337	20 6400	18 8467	17 0538	15 2614	13 4694	11 6777
50	09 8866	08 0958	06 3054	04 5155	02 7260	00 9369	.9899 1482	.9897 3598	.9895 5719	.9893 7844
60	.9891 9973	.9890 2106	.9888 4243	.9886 6384	.9884 8529	.9883 0677	81 2830	79 4986	77 7146	75 9310
70	74 1477	72 3649	70 5824	68 8003	67 0185	65 2371	63 4561	61 675$\bar{5}$	59 8952	58 1152
80	56 3356	54 5564	52 7775	50 9990	49 2208	47 4430	45 665$\bar{5}$	43 8883	42 111$\bar{5}$	40 3350
90	38 5589	36 7830	35 0075	33 2324	31 4575	29 6830	27 9088	26 1349	24 3614	22 5881
100	20 8152									

°C. (Int.)	00	10	20	30	40	50	60	70	80	90
	$\delta_t/\delta_0 = V_0/V_t = (1 + \alpha t)^{-1}$									
100	0.9820 8152	0.9803 1024	0.9785 4182	0.9767 7603	0.9750 1264	0.9732 5142	0.9714 9212	0.9697 3452	0.9679 7836	0.9662 2340
200	.9644 6940	.9627 1611	.9609 6327	.9592 1064	.9574 5796	.9557 0497	.9539 5142	.9521 970$\bar{5}$	.9504 4159	.9486 8478
300	.9469 2637	.9451 6608	.9434 0364	.9416 3880	.9398 7128	.9381 0082				

TABLE XIII

DENSITY OF MERCURY AT t° C.

$$\delta_t\,(\text{gm./ml.}) = \frac{\delta_0}{1 + \alpha t} = \frac{13.59546}{1 + \alpha t}.$$

°C. (Int.)	0	1	2	3	4	5	6	7	8	9
	Density, gm./ml.									
0	13.59 546	13.59 299	13.59 053	13.58 806	13.58 560	13.58 313	13.58 067	13.57 821	13.57 57$\bar{5}$	13.57 329
10	.57 083	.56 837	.56 591	.56 345	.56 099	.55 854	.55 608	.55 362	.55 117	.54 872
20	.54 626	.54 381	.54 136	.53 891	.53 645	.53 400	.53 155	.52 911	.52 666	.52 421
30	.52 176	.51 932	.51 687	.51 442	.51 198	.50 954	.50 709	.50 46$\bar{5}$	.50 221	.49 977
40	.49 732	.49 488	.49 244	.49 001	.48 757	.48 513	.48 269	.48 025	.47 782	.47 538
50	.47 29$\bar{5}$	.47 051	.46 808	.46 564	.46 321	.46 078	.45 83$\bar{5}$	.45 592	.45 349	.45 106
60	.44 863	.44 620	.44 377	.44 134	.43 891	.43 649	.43 406	.43 163	.42 921	.42 678
70	.42 436	.42 193	.41 951	.41 709	.41 467	.41 224	.40 982	.40 740	.40 498	.40 256
80	.40 014	.39 772	.39 530	.39 289	.39 047	.38 805	.38 564	.38 322	.38 080	.37 839
90	.37 597	.37 356	.37 11$\bar{5}$	.36 873	.36 632	.36 391	.36 149	.35 908	.35 667	.35 426
100	.35 185									

°C. (Int.)	00	10	20	30	40	50	60	70	80	90
	Density, gm./ml.									
100	13.35 185	13.32 777	13.30 373	13.27 972	13.25 57$\bar{5}$	13.23 180	13.20 788	13.18 399	13.16 011	13.13 625
200	.11 241	.08 857	.06 474	.04 091	.01 708	12.99 32$\bar{5}$	12.96 941	12.94 556	12.92 169	12.89 781
300	12.87 390	12.84 997	12.82 601	12.80 201	12.77 798	.75 391				

TABLE XIV

VOLUME OF UNIT MASS OF MERCURY AT t° C.

$$V_t\,(\text{ml./gm.}) = V_0\,(1 + \alpha t) = \frac{1 + \alpha t}{13.59546}.$$

°C. (Int.)	0	1	2	3	4	5	6	7	8	9
	Volume, ml./gm.									
0	0.073 5540	0.073 5673	0.073 5807	0.073 5940	0.073 6074	0.073 6207	0.073 6341	0.073 6474	0.073 6608	0.073 6741
10	687$\bar{5}$	7008	7142	7276	7409	7543	7676	7810	7944	8077
20	8211	834$\bar{5}$	8478	8612	8746	8880	9013	9147	9281	941$\bar{5}$
30	9549	9682	9816	9950	.074 0084	.074 0218	.074 0352	.074 0486	.074 0620	.074 0754
40	.074 0888	.074 1022	.074 1156	.074 1290	1424	1558	1692	1826	1960	2094
50	2228	2362	2496	2631	276$\bar{5}$	2899	3033	3168	3302	3436
60	3570	370$\bar{5}$	3839	3973	4108	4242	4377	4511	4646	4780
70	491$\bar{5}$	5049	5184	5318	5453	5587	5722	5857	5991	6126
80	6261	6396	6530	6665	6800	693$\bar{5}$	7070	7204	7339	7474
90	7609	7744	7879	8014	8149	8284	8419	8554	8690	882$\bar{5}$
100	8960									

°C. (Int.)	00	10	20	30	40	50	60	70	80	90
	Volume, ml./gm.									
100	0.074 8960	0.075 0313	0.075 1669	0.075 3028	0.075 4390	0.075 5755	0.075 7124	0.075 8496	0.075 9872	0.076 1252
200	.076 2637	.076 4026	.076 5419	.076 6818	.076 8221	.076 9630	.077 1045	.077 2466	.077 3893	.077 5326
300	.077 6765	.077 8212	.077 9666	.078 1127	.078 2596	.078 4073				

TABLE XV

MEAN COEFFICIENT OF THERMAL DILATION OF VITREOUS SILICA FROM 0° TO t °C.

$$\alpha\ {}^\circ\mathrm{C.}^{-1} \times 10^8 = \frac{V_t - V_0}{tV_0} \times 10^8.$$

$$= \frac{100\,(t + 157.281)}{0.0004225t^2 + 0.29362t + 137.32}. \qquad \begin{array}{l}(-150^\circ < t\ {}^\circ\mathrm{C.}\ (\text{thermodynamic}) < 0^\circ)\\ (0^\circ < t\ {}^\circ\mathrm{C.}\ (\text{International}) < +450^\circ)\end{array}$$

°C.	00	10	20	30	40	50	60	70	80	90
	α °C.$^{-1}$ × 10^8									
−100	51.06	42.93	34.47	25.67	16.54	7.08				
− 0	114.54	109.56	104.30	98.75	92.89	86.73	80.2$\bar{5}$	73.4$\bar{5}$	66.32	58.86
+ 0	114.54	119.23	123.66	127.83	131.7$\bar{5}$	135.43	138.87	142.10	145.11	147.92
+100	150.54	152.97	155.22	157.30	159.22	160.99	162.61	164.10	165.4$\bar{5}$	166.67
200	167.78	168.78	169.67	170.46	171.1$\bar{5}$	171.75	172.27	172.71	173.07	173.36
300	173.59	173.7$\bar{5}$	173.8$\bar{5}$	173.89	173.88	173.82	173.71	173.56	173.37	173.14
400	172.87	172.57	172.24	171.87	171.48	171.06				

TABLE XVI

TRUE COEFFICIENT OF THERMAL DILATION OF VITREOUS SILICA AT t° REFERRED TO 0 °C.

$$\alpha' = \frac{1}{V_0}\,\frac{dV}{dt} = \frac{d(\alpha t)}{dt}.$$

°C.	00	10	20	30	40	50	60	70	80	90
	α' °C.$^{-1}$ × 10^8									
−100	− 28.56	− 48.34	− 69.12	− 90.87	−113.56	−137.13				
− 0	+114.54	+104.4$\bar{5}$	+ 93.49	+ 81.64	+ 68.86	+ 55.12	+ 40.40	+ 24.69	+ 7.96	− 9.79
+ 0	114.54	123.79	132.25	139.96	146.94	153.24	158.89	163.93	168.39	+172.32
+100	175.74	178.70	181.21	183.31	185.03	186.39	187.43	188.17	188.63	188.83
200	188.80	188.55	188.11	187.49	186.70	185.76	184.69	183.5$\bar{0}$	182.20	180.80
300	179.31	177.7$\bar{5}$	176.12	174.42	172.68	170.89	169.06	167.20	165.31	163.40
400	161.47	159.53	157.58	155.62	153.66	151.70				

TABLE XVII

MEAN COEFFICIENT OF LINEAR THERMAL EXPANSION OF VITREOUS SILICA FROM 0° TO t °C.

$$\alpha_{\text{linear}}\ {}^\circ\mathrm{C.}^{-1} \times 10^8 = \frac{l_t - l_0}{t\,l_0} \times 10^8.$$

$$= \frac{100\,(t + 157.361)}{0.00126792t^2 + 0.88121t + 412.109}. \qquad \begin{array}{l}(-150^\circ < t\ {}^\circ\mathrm{C.}\ (\text{thermodynamic}) < 0^\circ)\\ (0^\circ < t\ {}^\circ\mathrm{C.}\ (\text{International}) < +450^\circ)\end{array}$$

°C.	00	10	20	30	40	50	60	70	80	90
	α_{linear} °C.$^{-1}$ × 10^8									
−100	17.04	14.33	11.51	8.58	5.54	2.39				
− 0	38.18	36.53	34.78	32.93	30.98	28.92	26.76	24.5$\bar{0}$	22.12	19.63
+ 0	38.18	39.7$\bar{5}$	41.22	42.61	43.92	45.14	46.29	47.37	48.37	49.31
+100	50.18	50.99	51.74	52.43	53.07	53.66	54.20	54.69	55.14	55.55
200	55.92	56.25	56.55	56.81	57.04	57.24	57.41	57.56	57.68	57.78
300	57.85	57.90	57.94	57.95	57.9$\bar{5}$	57.93	57.89	57.84	57.78	57.70
400	57.61	57.51	57.40	57.28	57.1$\bar{5}$	57.01				

TABLE XVIII

True Coefficient of Linear Thermal Expansion of Vitreous Silica at *t*° Referred to 0° C.

$$\alpha'_{\text{linear}} = \frac{1}{l_0}\frac{dl}{dt} = \frac{d\,(\alpha_{\text{linear}}\,t)}{dt}.$$

°C.	00	10	20	30	40	50	60	70	80	90
	α'_{linear} °C.$^{-1}$ × 10^8									
−100	− 9.49	−16.08	−23.00	$-30.2\bar{5}$	−37.81	−45.66				
− 0	+38.18	+34.82	+31.17	+27.23	+22.97	+18.39	+13.49	+ 8.25	+ 2.68	− 3.24
+ 0	38.18	41.27	44.09	46.65	48.98	51.08	52.96	54.64	56.12	+57.43
+100	58.57	59.55	60.39	61.09	61.66	62.12	62.46	62.71	62.86	62.93
200	62.92	62.83	62.69	62.48	62.22	61.90	$61.5\bar{5}$	$61.1\bar{5}$	60.71	$60.2\bar{5}$
300	59.75	59.23	58.69	58.12	57.54	56.94	56.34	55.71	55.09	$54.4\bar{5}$
400	53.81	53.16	52.51	51.86	51.20	50.55				

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AN EXPERIMENTAL STUDY OF THE ABSOLUTE TEMPERATURE SCALE

IX. THE DETERMINATION OF THE CAPILLARY DEPRESSION AND MENISCUS VOLUME OF MERCURY IN A MANOMETER

By James A. Beattie, B. Edwin Blaisdell, and Joseph Kaye

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1. Introduction

In precise gas thermometric investigations two of the significant factors entering into the reduction of the data are: (1) the capillary depression correction, that is, the difference between the capillary depression of mercury in the long and short arms of the manometer, and (2) the dead space correction for the co-volume of the mercury meniscus, that is, the correction for the temperature and variation of the volume of the gas below a horizontal plane tangent to the crown of the meniscus in the short arm (the volume of a cylinder of height equal to that of the meniscus and diameter equal to the bore of the manometer tube minus the volume of the meniscus). The capillary depression and the volume of the meniscus may be expressed in terms of the following quantities which can be determined experimentally: (1) the bore of the manometer tube, (2) the height of the meniscus, and (3) the capillary constant of mercury. The present paper deals with methods of measurement of the bore of the tube, the elevations of the crown and bottom of the meniscus, and the determination of the capillary constant of mercury in situ.

Since capillary depression decreases and meniscus covolume increases with increasing bore of tube, the selection of the manometer tube represents a compromise. Most investigators[1] have used tubes between 1.5 and 2.0 cm. bore.

Let δ_1 be the capillary depression in the long arm of the manometer and δ_2 the depression in the short arm. The capillary depression correction is $\delta_1 - \delta_2$. In general the long arm of the manometer is evacuated so that the height of meniscus and δ is less than in the short arm which contains the thermometric gas. For tubes of 2.0 cm. bore, δ_1 and δ_2 are each of the order of 0.04 mm., $\delta_1 - \delta_2$ of the order of 0.01 mm., and the maximum variation from the least to the greatest value of $\delta_1 - \delta_2$ is about 0.005 mm.; where the capillary constant for mercury is taken to be 0.266 cm. The reported measurements[2] on capillary depressions are not in agreement due probably to differences in the capillary constant of the mercury used. A small amount of impurity has a relatively large effect on the value of the constant.

The correction δ_5 to be added to the observed pressure p' for the variation ΔV_c in the meniscus covolume V_c from some arbitrarily selected standard value (so chosen that ΔV_c is always positive) is

$$\delta_5 = p' \frac{\Delta V_c}{V},$$

where V is the total volume (bulb and dead space) of the gas thermometer at standard conditions; and the correction δ_6 for the deviation of the Kelvin temperature T_c of the gas in the covolume from that T_b of the bulb is

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[1] For a description of our gas thermometer system and a list of references to the apparatus of other investigators see J. A. Beattie, D. D. Jacobus, J. M. Gaines, Jr., M. Benedict, and B. E. Blaisdell, Proc. Am. Acad. Arts Sci., **74**, 327–342 (1941).

[2] W. Heuse, Z. Instr., **47**, 324 (1927); W. Cawood and H. S. Patterson, Trans. Faraday Soc., **29**, 514–523 (1933).

$$\delta_6 = p' \frac{V_c}{V}\left(\frac{T_b}{T_c} - 1\right).$$

For tubes of 2.0 cm. bore V_c is of the order of 0.15 ml. and the maximum value of ΔV_c is about 0.02 ml. When $p' = 1366$ mm., $V = 1000$ ml., $T_b = 373$, and $T_c = 298$, δ_5 is about 0.03 mm. and δ_6 about 0.05 mm. The measurements of the volumes of mercury menisci by Scheele and Heuse[3] and by Keesom, van der Horst, and Taconis[3] agree to about 1%, while those by Palacios[3] differ from the average of these by approximately 5%.

In the past it has been the usual practice to omit the capillary depression correction or to determine it from tables[4] expressing the correction as a function of tube bore and meniscus height. The covolume of the meniscus was generally assumed to be constant or to be given by one of the published tables. Keesom, van der Horst, and Taconis[5] determined the meniscus volume at each gas thermometer measurement from an X-ray shadowgraph of the meniscus, the volume being computed as the sum of a number of spherical segments whose dimensions were derived from measurements of the plate. This gives the correct covolume for each measurement independent of any assumption concerning the capillary constant of mercury.

In our measurements we determined: the bore of the manometer tubes, the meniscus height for each measurement, and the capillary constant of the mercury in the manometer. The methods employed for determining each quantity are described in the present paper. The tables of the properties of menisci that we used have been prepared[6] by numerical integration of Laplace's differential equation for the equilibrium meridian of a fluid drop of axial symmetry in a gravitational field.

2. Determination of the Bore of Manometer Tubes

The bore of the short arm just below the index and that of the long arm at various heights should be measured after the tubes are in place. The former affects the value of meniscus covolume read from the tables as well as the computed capillary depression correction and should be known more accurately than the latter. The methods found feasible are:

(a) The measurement of the diameter of the image of the mercury column on photographic plates taken with X-rays. This is described in a later section of the present paper.

(b) The determination of the volume (from mass and temperature) and length of a column of mercury about 0.5 cm. high which was run out of the tube into a weighing bottle. Meniscus heights were measured before and after the mercury was run out and correction made for the difference in meniscus volumes.

(c) The determination of the volume (from a calibrated mercury injector[1]) and length of a column of mercury about 0.5 cm. high withdrawn into the injector, correction being made for meniscus volumes.

In all calibrations mercury was always drawn or forced into the manometer tubes from the bottom and the tubes were evacuated during filling. During the measurements the tubes were filled with nitrogen or air to one atmosphere pressure. The tubes were shaken before and after withdrawal of mercury so that meniscus heights were approximately the same at each reading.

All three methods agreed on the diameter of 2.0 cm. bore tubes to ± 0.1%. An error of 0.1% in the bore introduces an error of 2×10^{-4} mm. in the computation of the capillary depression and 2×10^{-4} ml. in the covolume of the meniscus.

3. Determination of the Elevations of the Crown and Bottom of a Mercury Meniscus

When only a few pressures are to be read and the approximate positions of the mercury meniscus in the long arm of the manometer are known, glass fibers[7] or platinum wires[8] may be sealed in with their bent-down points at the desired positions and the mercury brought into optical contact with the point by a slight adjustment of the dead space volume. We have not used this method.

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[3] K. Scheel and W. Heuse, Ann. der Physik, (4) **33,** 291–295 (1910); W. H. Keesom, Miss H. van der Horst, and K. W. Taconis, Kamerlingh Onnes Lab., Univ. of Leiden, Comm. No. **248a,** 5 pp. (1937); J. Palacios, Physik. Z., **24,** 151–155 (1923).

[4] In some cases the tables were prepared from the equation of T. Lohnstein, Ann. der Physik, (4) **33,** 296–307 (1910). For the capillary constant of mercury the value 0.25 cm. was usually used.

[5] W. H. Keesom, Miss H. van der Horst, and K. W. Taconis, Kamerlingh Onnes Lab., Univ. of Leiden, Comm. No. **230d,** 9 pp. (1933–4); see also Comm. No. **248a,** 5 pp. (1937).

[6] B. E. Blaisdell, J. Math. Phys., **19,** 186–245 (1940).

[7] J. T. Howarth and F. B. Burt, Trans. Faraday Soc., **20,** 544–549 (1924).

[8] W. Heuse and J. Otto, Ann. der Physik (5) **2,** 1012–1030 (1929).

When elevations are read by means of a vertical comparator and scale hung at the same optical distance from the objective of the telescope as the axis of the manometer tubes, the method of illumination of the meniscus has an important effect on the apparent elevation of the crown or bottom.

Four methods of illumination of the crown have been studied. In all investigations the room was darkened and the only source of light was in back of the manometer tubes. The methods are:

(1) Diffuse light coming from behind the manometer and a paper having diagonal black rulings placed immediately behind the tube.[9] This method has been found to be unsatisfactory for precision work.[10]

(2) Diffuse light coming from behind the manometer and a shield shaped to fit the back half of the manometer tube, the bottom of the shield[11] being a fixed distance above the crown of the meniscus thus forming a horizontal slit. The apparent elevation of the crown is a function of the height of the slit.[12]

(3) Parallel light,[5] produced by a spherical lens with a small illuminated disk at its principal focus, coming from behind the meniscus, with or without a shield. The apparent elevation of the crown is independent of slit width but the lens effect of the manometer tube causes some difficulties.[12]

(4) Light[11] that behaves as parallel light in vertical planes and as diffuse light in horizontal planes, produced by a cylindrical lens placed with its elements horizontal and an illuminated slit at its principal focus, coming from behind the manometer, with or without a shield. The apparent elevation of the crown of a meniscus read with this method of illumination is independent[12] of: the relative elevation of the axis of the telescope and the crown provided the telescope is focused on the axis of the manometer tubes, vertical displacement and variation in zenith angle of the optical system provided the beam of light does not slope downward, lateral displacement and variation in azimuthal angle of the optical system, and slit height.

With the last method of illumination which is the most satisfactory so far investigated the image of the meniscus viewed through the eyepiece of the telescope is inverted and a dead black shadow against a light background. The cross-hair in the telescope was elevated by turning the micrometer screw until a narrow band of light, perhaps 0.005 mm. high at the center, remained visible above its upper edge. An experienced observer remembers the width of this band and is able to set the cross-hair on the meniscus with a probable error of a single observation of 0.001 mm. (5 readings).

Two methods of illumination of the bottom of the meniscus have been employed.

(a) Method (4) described above. With this type of illumination the glass tube surrounding the mercury column appears to an observer dark where mercury touches the glass and light where no mercury touches, these regions being separated by fine intensely black horizontal lines, one on each side of the tube, in the plane of the circle of contact of the mercury with the glass, that is, in the plane of the bottom of the meniscus. The cross-hair in the telescope was set on the crown of the meniscus and on the right and left black lines in the glass so that the height of the narrow band of light remaining visible above its upper edge was the same in each case. The mean of the micrometer readings when the hair-line was set on the right and left black lines was taken to be the elevation of the bottom of the meniscus. An experienced observer can read the height of a meniscus—micrometer reading for setting on crown minus mean reading for bottom—by the means just described, Method (4, a), with a probable error of 0.003 mm. (5 readings). The variation of the experimental conditions mentioned above under Method (4) produces no effect on the observed height.

(b) When the magnification of the eyepiece of the telescope is too great to permit viewing the entire meniscus without rotation of the bar of the comparator we read the bottom of the meniscus with diffuse illumination from in front of the manometer tube. A piece of frosted glass 2 cm. high by 1 cm. wide placed vertically was lighted from behind by a small flashlight bulb enclosed in a light-tight box. The window faced the manometer tube and its center was in the same horizontal plane as the bottom of the meniscus, about 16 cm. in front of the axis of the manometer tube but displaced laterally about 2 cm. from the axis of the telescope so as to be just outside of the field of view. With this method of illumination an observer sees in the upper part of the field of view of the telescope a broad band of bright light one or more millimeters wide against a dark background where the mercury touches the glass tube and acts as a vertically placed cylindrical mirror. The bright band tapers at its bottom, being trapezoidal in form for the lower 0.3 millimeter or so, and is continued downward as a much less intense band of light caused by reflection from the glass surfaces. The bottom edge of the trapezoid, which separates the bright and the less intense portions of the band, is a fairly narrow dark, but not black, horizontal line. The cross-hair in the telescope was elevated until its upper edge coincided with the bottom of the bright band of light. There was thus a lack of symmetry in the setting of the cross-hair on the crown and on the bottom of the meniscus and this could not be overcome since the crown appeared dark against a light background and we moved the hair-line up until a narrow band of light remained between the top of the cross-hair and the shadow of the meniscus, while the bottom of the bright band appeared light against a darker background and we moved the hair-line up until its top edge coincided with the bottom of the bright band. For a fixed position of meniscus and telescope an experienced observer could read the height of a meniscus by this method of illumination, Method (4, b), with a probable error of 0.005 mm. (5 readings). However the apparent height depended on the relative elevations of the bottom of the meniscus and the axis of the telescope.

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[9] W. C. Röntgen, Pogg. Ann. der Physik, **148,** 580–624 (1873).

[10] S. C. Collins and B. E. Blaisdell, Rev. Sci. Instr., **7,** 359 (1936).

[11] See Fig. 4, ref. 1.

[12] S. C. Collins and B. E. Blaisdell, Rev. Sci. Instr., **7,** 213–214 (1936).

Since the telescope was in focus for the axis of the manometer tube it was out of focus for the front point of the bottom of the meniscus by a distance equal to the radius of the manometer tube so that the image of the band of light reflected from the cylindrical column of mercury was in a vertical plane farther away from the objective than the plane of the cross-hair; the image of the crown of the meniscus was of course in the plane of the cross-hair. The observed elevation of the bottom of the meniscus was in error; that of the crown, correct.

Let:

h = true height of meniscus determined by Method (4, a).

h' = apparent height determined by Method (4, b).

r = internal radius of manometer tube.

d = horizontal distance from first principal plane of the objective to axis of manometer tube, the image of an object in the axis being in the vertical plane of the cross-hair.

δ = vertical distance from the axis of the telescope to a horizontal plane through the bottom of the meniscus, positive if the plane is below the axis, negative if above.

Δ = radius of the entrance pupil of the telescope (the objective).

ε = error due to lack of symmetry of setting of cross-hair on the crown and bottom of the meniscus.

If we interpret the apparent bottom of the trapezoid of the bright band of light seen in the telescope as being the line of intersection with the vertical plane of the hair-line of the rays of light that are reflected from the top edge of the cylinder of mercury and pass through the lowest point of the objective, we obtain:

$$h = h' - \frac{r}{d-r}\delta + \frac{r}{d-r}\Delta - \varepsilon, \qquad (1)$$

where the second term on the right side of the equation is the correction for the magnification of the distance from the axis of the telescope to the bottom of the meniscus, the third term that for the circle of confusion determined by the ray of light from the bottom of the meniscus that passes through the lowest point of the objective, and the fourth that for the lack of symmetry of setting the hair-line on the crown and bottom of the meniscus. The last two effects cannot be separated since we do not know exactly where within the circle of confusion the hair-line is set, even though the setting can be made reproducibly. For a given observer and apparatus in which the only variable is δ, Eq. (1) may be written:

$$h = h' - \frac{r}{d-r}\delta' + \Delta', \qquad (2)$$

where δ' is the apparent value of δ as measured in the telescope by Method (b) illumination—micrometer reading when hair-line is set on bottom of bright band of light minus reading when set on axis of telescope—and Δ' is an empirical constant (positive or negative) to be determined experimentally by measurement of the apparent height h' of some one meniscus for a series of values of δ' and determination of the true height by the Method (4, a) or from an X-ray shadowgraph.

For a manometer tube of 2 cm. bore the axis of which was 62.3 cm. distant from the telescope objective we found in one instance:

$$h = h' - .0163\delta' - .004 \qquad (3)$$

for h, h', and δ' in mm. Thus for this observer and experimental equipment the correction to the observed height h' of the meniscus was $-.004$ mm. for $\delta' = 0$, -0.037 mm. for $\delta' = 2$ mm., and -0.069 mm. for $\delta' = 4$ mm. In other circumstances quite different values of Δ' were obtained, the value being sometimes positive.

4. DETERMINATION OF THE CAPILLARY CONSTANT OF MERCURY

Consider a glass tube with its axis vertical containing mercury. Let:

r = radius (cm.) of the tube.

h = height (cm.) of the mercury meniscus.

h_0 = capillary depression (cm.) of the mercury in the tube.

x, y = Cartesian coördinates (cm.) of a point on the surface of the meniscus; the origin is at the intersection of the axis of the manometer tube with the surface of the meniscus, y is the vertical distance (measured downward along the axis) to a horizontal plane passing through the point in question, and x is the radial distance measured in this plane from the axis to the point. When the point is in the bottom of the meniscus, $y = h$ and $x = r$.

ϕ = angle made by a tangent to the meniscus in the meridian plane with the horizontal.

v = volume (cm.^{3}) of the meniscus above a horizontal plane through the bottom.

a = capillary constant (cm.) of mercury.

$$H_0 \equiv \frac{h_0}{a}\,;\; X \equiv \frac{x}{a}\,;\; Y \equiv \frac{y}{a}\,;\; V \equiv \frac{v}{a^3}\,;$$

these four quantities being dimensionless ratios.

Tables[6] have been published listing:

I : tan ϕ (or cot ϕ) as a function of H_0 and Y (Blaisdell's Tables II and III; pp. 204–207),

II : X as a function of H_0 and Y (Blaisdell's Table IV, pp. 208–211),

III : Y as a function of H_0 and X (Blaisdell's Table V, pp. 212–213),

IV : H_0 as a function of X and Y (Blaisdell's Table I, pp. 218–221),

V : V as a function of X and Y (Blaisdell's Table II, pp. 222–225).

We shall designate these tables by the Roman numerals I to V given at the left.

From these tables the value of the capillary constant a of mercury in a manometer may be determined by three independent methods which involve only observations that can be made on the system in situ.

When the value of a is known we can by multiplication convert Tables IV and V to express:

h_0 as a function of h and r,

v as a function of h and r,

for the mercury in the manometer. By inverse interpolation h_0 and v can be expressed for integer values of the arguments h and r.

Tables expressing h_0 and v as functions of h and r for various values of a will be published shortly. When a is known for the mercury in a manometer these tables will afford a simple means of finding h_0 and v corresponding to measured values of h and r.

(a) *From Measurement of Meniscus Volumes*

The quantities r, v, and h are measured and used to compute a from Table V in which values of the function V $(= v/a^3)$ are tabulated, the rows being for constant values of the argument X $(= r/a)$ and the columns for constant Y $(= h/a)$.

Experimental. The radius of the manometer tube was measured.

A low meniscus was produced by withdrawal of mercury into the calibrated injector[1] and its height h_1 measured. Sufficient mercury was injected to increase the meniscus height 0.05 to 0.10 mm.; and the volume $v_2 - v_1$ of mercury introduced and the height h_2 of the meniscus measured. The experiment was continued until the elevation of the bottom of the meniscus changed, indicating that slipping had occurred.

The measured quantities are thus: r, h_i, Δv_i $(= v_i - v_1)$ $(i = 1, 2, \ldots n)$ where v_1 is unknown.

Calculations. 1. Select the row X' in Table V having the value of the argument closest to r/a where a is an assumed value (say 0.260 cm.) for the capillary constant of mercury. Compute from the experimental data:

$$a' = r/X',$$

$$Y_i' \text{ (obs.)} = h_i/a', \qquad (i = 1, 2, \ldots n)$$

Compute from row X' of Table V:

V_i' (calcd.) corresponding to Y_i' (obs.) (by direct interpolation), $(i = 1, 2, \ldots n)$

$\Delta v_i'$ (calcd.) $= a'^3\,[V_i'$ (calcd.) $- V_1'$ (calcd.)$]$ $(i = 2, 3, \ldots n)$

$\nu_i = \Delta v_i$ (obs.) $- \Delta v_i'$ (calcd.), $(i = 2, 3, \ldots n)$

$\Sigma_i\,|\nu_i|$

2. Repeat the Process 1 using the same experimental data—r, h_i, Δv_i—but the rows X'', X''', etc. of Table V immediately above and below X', thus obtaining the values a'', a''', etc., and the corresponding sums $\Sigma_i|\nu_i''|$, $\Sigma_i|\nu_i'''|$, etc. of the absolute values of the deviations.

Plot $\Sigma_i|\nu_i|$ as ordinate against a as abscissa or express $\Sigma_i|\nu_i|$ as a quadratic function of a. The value of a for the minimum $\Sigma_i|\nu_i|$ is the capillary constant of mercury in the manometer.

Accuracy. This method gave values of a with a probable error of 5% (5 complete sets of observations). The value of a agreed with that determined from the X-ray shadowgraph method within the probable error.

This method is the least accurate of the three described in this paper; but it is the simplest from the viewpoint of both experimental work and computation. The calculation tends to eliminate any error caused by differences in the methods of reading the elevations of the crown and bottom of the meniscus.

In ground and polished glass tubes a high meniscus cannot be obtained so that the possible variation of h is limited and consequently the precision of the method is decreased.

(b) *Method of Eötvös*

In the method of Eötvös[13] the quantities ϕ and y are determined for a mercury meniscus by an optical method and h_0 computed from h and r. These quantities are used to compute a from Table I in which values of the function tan ϕ (or cot ϕ) are tabulated, the rows being for constant values of the argument H_0 $(= h_0/a)$ and the columns for constant Y $(= y/a)$. The computations are simplified by the fact that tan ϕ varies only slowly with H_0. Since H_0 cannot be measured directly there is obtained from Table IV by interpolation a provisional value; this being the value of the function H_0 for the arguments X $(= r/a)$ and Y $(= h/a)$. The latter are computed from the radius r of the manometer tube, the height h of the meniscus, and an assumed value of a.

Experimental. The lower half of the objective of the telescope was covered with black paper up to a horizontal line 1 mm. below the axis. The telescope was leveled and set so that the image of the crown of the meniscus was on the axis of the telescope and in the vertical plane of the cross-hair.

The illuminating system for the measurements made by the Eötvös method consisted of a 100-watt bulb enclosed in a box 15 cm. wide. The bottom and the front of the box were covered with translucent paper to produce a source of diffuse light. The upper portion of the paper covering the front was made opaque with black ink. The box was placed behind the manometer with the front facing the telescope so as to illuminate the meniscus by diffuse light coming from behind and with the bottom edge of the opaque portion of the front cover horizontal. The box could be raised or lowered vertically and its front cover was a distance B (large in comparison with the radius of the manometer tube, say 100 cm.) behind the axis of the tube. The distance C from the crown of the meniscus to the bottom edge of the blackened portion of the front was varied from about 25 to 125 cm. in increments of 5 or 10 cm. Viewed through the telescope, a meniscus illuminated in this manner appeared very similar to one illuminated by Method (2) described in an earlier section of this paper, that is, black against a light background. The portion of the meniscus reflecting light into the telescope was invisible or practically invisible against the background of diffuse light coming from the bottom of the light-box. The apparent crown of a meniscus so illuminated is interpreted as the point P on the meniscus and in the plane defined by the axes of the manometer tube and the telescope at which light from the highest point of the front of the light-box (a point just below the bottom of the blackened portion) was reflected horizontally into the telescope. Actually some light was reflected into the telescope from a point slightly below P (about .001 mm. below P for a tube of 1 cm. radius) since the objective was not covered all the way to the axis; but the sharpness of the edges of the shadow of the meniscus indicates that the amount of light reflected into the telescope decreased rapidly below some point which we took to be the point P. The smallest value of the distance C was so chosen that P was about three quarters of the distance from the axis to the inside wall of the manometer tube.

The radius r of the manometer tube was measured.

A stable meniscus was produced by shaking the tube and its true height h measured by Method (4, a) described above. Let P_0 be the true elevation of the crown determined by this method of illumination.

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[13] F. Eötvös, Wied. Ann. der Physik, **27,** 448–459 (1886).

The apparent elevation of the crown, that is, the elevation of the point P_1, was measured by use of the illuminating device just described with the bottom of the blackened portion of the paper covering the front of the light-box at a height C_1 above the crown. The process was repeated for a series of values of C. The shape of the meniscus must not change throughout the entire series of observations.

The measured quantities are thus: r, h, B, C_i and P_i ($i = 1, 2, . . . n$).

Calculations. From r, h, and a provisional value of a (say 0.260 cm.) compute X ($= r/a$) and Y ($= h/a$) and read from Table IV the corresponding provisional value of the function H_0. *All of the computations* described below are made by use of the row H_0 for which the value of the argument H_0 is nearest the provisional value.

1. In order to calculate y_i and ϕ_i we must know the x_i coordinate of the point P_i. From row H_0 of Table II compute by interpolation the value of the function X_i for the argument Y_i [$= (P_0 - P_i)/a$] and hence find x_i ($= X_i a$) for the points $i = 1, 2, . . . n$.

Now compute the value of y_i by Eq. (1):

$$y_i = (P_0 - P_i) - \frac{x_i}{d - x_i}(P_0 - P_i), \qquad (i = 1, 2, . . . n) \quad (4)$$

where Δ and ε have been set equal to zero. Compute ϕ_i from the relation:

$$\phi_i = \frac{1}{2}\tan^{-1}\frac{C_i + y_i}{B_i + x_i}, \qquad (i = 1, 2, . . . n) \quad (5)$$

and read tan ϕ_i from trigonometric tables.

From row H_0 of Table I compute:

Y_i (calcd.) corresponding to tan ϕ_i (by inverse interpolation). ($i = 1, 2, . . . n$).

By the method of least squares express y_i as a linear function of Y_i (calcd.). The slope dy_i/dY_i (calcd.) is a.

2. If the calculated value of a is greatly different from the provisional value used to compute H_0, repeat Process (1) using the value just obtained for evaluating a new H_0.

Accuracy. This method gave values of a with a probable error of 1.5% (5 sets of measurements) for mercury in a manometer tube of 2 cm. bore. The mean agreed with the value of a given by the X-ray shadowgraph method within the probable errors of the two methods.

We computed a from one set of measurements for mercury in a tube of 2 cm. bore using as provisional values 0.260 and 0.255 cm. for a and using the rows 0.010 and 0.009 for H_0 with each provisional a. The total spread of the calculated values of a was 0.15%.

The maximum effect of two of the three optical uncertainties can be estimated. For a manometer tube 2 cm. bore and with a telescope with its objective 62.3 cm. from the axis of the tube and covered to within 1 mm. of the axis we made measurements in which y varied from 0.300 to 0.709 mm. and x from 7.456 to 9.078 mm. The magnification correction, which we applied, varied from − 0.0036 to − 0.0105 mm. The maximum value of the correction caused by the circle of confusion varied from + 0.0121 to + 0.0148 mm.; and the correction for the fact that light was reflected into the telescope from a point lower than that which caused a ray from the top of the light box to be reflected horizontally varied from − 0.0010 to − 0.0005 mm. The setting error could not be determined but the correction was opposite in sign to that for the circle of confusion and probably constant. It will be noted that the method of computing a eliminates any constant error in y.

(c) *X-ray Shadowgraph Method*

The quantities x and y are determined for the profile curve of a mercury meniscus from an X-ray photograph, and h_0 computed from h and r. These quantities are used to compute a from Tables II and III in which the values of the function X ($= x/a$) (Table II) or Y ($= y/a$) (Table III) are tabulated, the rows being for constant values of the argument H_0 ($= h_0/a$) and the columns for constant Y (Table II) or X (Table III). Since H_0 cannot be measured a provisional value is obtained from Table IV by interpolation; this being the value of H_0 for the arguments X ($= r/a$) and Y ($= h/a$) where r and h are measured and the value of a assumed.

Experimental. A photograph of the profile of the meniscus was taken on a plate placed 1.5 cm. in front of the axis of the manometer tube and perpendicular to a beam of X-rays from an aperture 1 mm. in diameter, 1.5 meters behind the manometer tube. The resulting photograph was a shadowgraph of the meniscus and the mercury column without noticeable penumbra. The edge of the dark field surrounding the light image of the meniscus was sharply defined except for a distance of about 0.3 mm. from the right and left ends where the mercury layer presented to the beam of X-rays was thin and the glass layer thick. The profile of the glass tube was also plainly visible but the contrast was not so sharp as for the mercury.

The plate was aligned on an astronomical plate comparator and the x, y coordinates of the profile curve measured to 0.0001 cm. from the bottom of the meniscus on one side to the bottom of the other, the readings being spaced so that $\Delta x = 1$, 0.5, 0.3, or 0.2 mm. whichever made $\Delta y \overset{=}{<} 0.2$ mm. At the same time the bore and outside diameter of the manometer tube were measured. The outside diameter of the tube was also measured by a micrometer.

The measured quantities are thus: r, h, x_i, y_i $(i = 1, 2, \ldots n)$; all of which are subject to correction for lack of alignment of the plate on the comparator.

Calculations. Plot the measured coördinates of the profile curve on translucent paper to a scale 100 times natural size in the y direction and 25 times in the x direction. Hold the paper to the light and fold so that the two halves of the curve coincide as closely as possible, the two points nearest the bottom of the meniscus on each side being neglected since reproducible settings to 10^{-4} cm. cannot be made in this region. It may happen that there is one more point near the bottom of the meniscus on one side than on the other; if so reject the point nearest the bottom so that there are the same number of points far removed from the axis of the manometer tube on each side. These rejected points are not to be used in any of the following calculations.

The angle θ which the fold makes with the y axis of the cross-section paper is to the first approximation the angle through which the coördinate axes must be rotated and the intersection of the fold with the plot of the profile curve is to the first approximation the proper origin of the coördinate system. The angle θ is positive if the fold slopes upward to the left.

Correct each observed x_i and y_i by the relations:

$$x_i\,(\text{corr.}) = [(x_i - x_0) + (y_i - y_0)\tan\theta]\cos\theta, \qquad (i = 1, 2, \ldots n) \qquad (6)$$

$$y_i\,(\text{corr.}) = [(y_i - y_0) - (x_i - x_0)\tan\theta]\cos\theta,$$

where x_0, y_0 are the coördinates of the proper origin; and multiply each x_i (corr.), y_i (corr.) by the scale factor f which can now be determined as

$$f = \frac{\text{external dia. of tube from micrometer meas.}}{\text{external dia. measured on plate} \times \cos\theta}.$$

The resulting values are: r, h, x_i (from $-r$ to $+r$), y_i (from 0 to h) $(i = 1, 2, \ldots n)$; all of which are corrected to the first approximation for the lack of alignment of the plate on the comparator, the location of the proper origin, and the magnification of the photograph.

Enlarge by interpolation Tables II and III so that there is a row for each increment of 0.0002 in the argument H_0 in the range to be used ($H_0 =$ 0.006 to 0.012 for tubes about 2.0 cm. bore), and a column for each increment of 0.004 in Y (Table II) and 0.025 in X (Table III). The enlarged tables can now be used by linear interpolation.

1. From r, h, and a provisional value of a (say 0.2600 cm.) read from Table IV a provisional value of H_0 corresponding to X $(= r/a)$ and Y $(= h/a)$. Select the row H_0' in Tables II and III having the value of the argument closest to the provisional value just obtained and take $a_1' =$ 0.2600 cm. Compute from the experimental data:

$$X'_{i1}\,(\text{obs.}) = x_i/a_1', \qquad (i = 1, 2, \ldots n)$$

$$Y'_{i1}\,(\text{obs.}) = y_i/a_1'. \qquad (i = 1, 2, \ldots n)$$

Compute from row H_0' of Tables II and III: Y'_{i1} (calcd.) corresponding to X'_{i1} (obs.) (by direct or inverse interpolation), $(i = 1, 2, \ldots n)$

$$\nu'_{i1} = Y'_{i1}\,(\text{obs.}) - Y'_{i1}\,(\text{calcd.}) \qquad (i = 1, 2, \ldots n)$$

The final correction for alignment is now to be made. Correct each x_i, y_i by Eq. (6) using

$$\theta = \tan^{-1}\frac{1}{2}\left[\left(\frac{\Sigma_i\,\nu'_{i1}}{\Sigma_i X'_{i1}}\right)_{x\ \text{positive}} + \left(\frac{\Sigma_i\,\nu'_{i1}}{\Sigma_i\,X'_{i1}}\right)_{x\ \text{negative}}\right]. \qquad (7)$$

$$x_0 = 0,$$

$$y_0 = \frac{a_1'}{3}\sum_1^3{}_i\,\nu'_{i1},$$

the last summation being taken for the three points nearest the origin of the coördinate system. In general this final correction will not affect the fourth decimal place in x_i, y_i but serves as a check on the earlier adjustments.

2. Repeat Process (1) if necessary and form:

$\Sigma_i|\nu'_{i1}|$ and $\Sigma_i\,\nu'_{i1}$ corresponding to H_0' and a_1',

$\Sigma_i|\nu'_{i2}|$ and $\Sigma_i\,\nu'_{i2}$ corresponding to H_0' and a_2',

etc.;

where all calculations are to be made from the same row H_0' but a is varied in increments of 0.0002 cm. Plot $\Sigma_i|\nu_i'|$ and $\Sigma_i\,\nu_i'$ each as ordinates against a' as abscissa. The value of a' and $\Sigma_i|\nu_i'|$ for which $\Sigma_i \nu_i' = 0$ are recorded; a' is the capillary constant of the mercury if H_0' happens to be the correct capillary depression of the mercury in the manometer.

3. Repeat Process (2) using the same experimental data—x_i, y_i corrected by Process (1)—but the rows H_0'', H_0''', etc., above and below H_0' in the enlarged table thus obtaining a series of simultaneous value of a and $\Sigma_i|\nu_i|$.

4. Plot $\Sigma_i|\nu_i|$ against a and read the correct value of the capillary constant corresponding to the minimum value of $\Sigma_i|\nu_i|$.

Accuracy. This method gave values of a with a probable error of 0.5% (3 plates). The average difference $n^{-1} \overset{n}{\underset{1}{\Sigma_i}} |Y_i\,(\text{obs.}) - Y_i\,(\text{calcd.})|$ in the fit of the curves was 0.00034 cm. (3 plates).

The last method is by far the most accurate and the most laborious. Much of the work is eliminated if an approximate value of a is known. This may be obtained by either of the first two methods described.

Acknowledgment. We wish to express our thanks to the staff of the Harvard Observatory for making available to us a comparator for measuring the X-ray plates.

5. SUMMARY

The errors introduced into gas thermometric measurements by uncertainties in the capillary depression of mercury and in the volume of the meniscus in the short arm of the manometer are discussed. It is brought out that accurate knowledge of the bore of the manometer tubes, heights of mercury menisci, and the capillary constant of the mercury in the manometer is required to make the necessary corrections.

Methods of determination of the bore of manometer tubes and the elevations of the crown and bottom of a mercury meniscus are discussed.

Three experimental methods for determination of the capillary constant of mercury in manometers which are in use are given.

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FREEZING PARAMETERS AND COMPRESSIONS OF TWENTY-ONE SUBSTANCES TO 50,000 kg/cm².

By P. W. Bridgman

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Introduction

In a preceding paper[1] the technique has been developed for measuring the compression of the more compressible substances up to 50,000 kg/cm^2 and applied to some 46 solid materials. In this paper the method is extended to 21 substances which are liquid under normal conditions; all of these 21 substances are organic except water. The object of this investigation is two-fold. It is in the first place to determine the melting parameters over a wider range than that previously explored,[2] which, except in the case of water, was 12,000 kg/cm^2. Apart from the intrinsic interest of obtaining numerical values in the wider range, there is at present some little theoretical interest in making such an extension, because recently the question has been brought up again of the ultimate course of the melting curve and the possibility of a critical point between liquid and solid.[3] In the second place it was desired to obtain as extensive measurements as possible of the p-v-t relations of both liquid and solid phase of the same substance. In spite of the great number of previous determinations of the p-v-t relations of solids and liquids, almost nothing has been done on both liquid and solid phases of the same substance, so that little is known of the change in thermodynamic properties produced by freezing.

Method

The technique of the previous work had to be modified to permit in the first place the handling of liquids instead of solids, and in the second place the use of a wider temperature range.

It was hopeless, within the limitations imposed by the magnitude of the pressure range and the small size of the apparatus, to attempt to pack the piston of the pressure vessel against leak by a liquid directly in contact with it. The liquid was accordingly sealed into a collapsible capsule of lead. After much trial the form of the capsule shown in Figure 1 was adopted. This is originally made in two pieces A and B, which are then fused together. Various attempts at soldering were without success. Fusing together

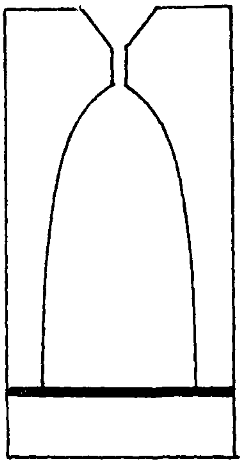

Fig. 1. The lead capsule for containing the liquids. The opening at the top is sealed by a lead plug fused with a condenser discharge.

is accomplished in an atmosphere of hydrogen. The bottom disc B is melted in a cup shaped mold in a miniature electric furnace. The part A is mounted in a holder by which it may be rotated about its vertical axis, and which may also be displaced vertically. When B is melted A is brought down until its lower edge dips into the molten metal, and it is then spun about its vertical axis until it is completely wet by the liquid metal and good contact made, as shown by the liquid lead climbing up the side of A. All this takes place in a stream of dry hydrogen. Filling is accomplished through the fine hole in the top by immersing the capsule under the liquid and applying and removing a vacuum several times and finally boiling the liquid. The seal is made electrically. A pointed lead wire is driven by a light hammer blow into the depression at the top of A. The wire and A are attached to the two coatings of a previously charged condenser so that a discharge takes place, fusing the lead locally, just before mechanical contact occurs. The soundness of the seal is tested by placing the sealed capsule under water in a test tube, which is heated sufficiently above the boiling point of the liquid to visibly distend the capsule. After the test the capsule is restored to shape by squeezing in the wire chuck of a lathe. The quantities of lead and liquid were determined by weighing, both before inserting in the pressure apparatus and after the run, as a check. The quantity of liquid was of the order of 0.2 or 0.3 gram, and the checks indicated an accuracy of 0.001 gram or better. In addition to weight of lead and liquid, the weights were also always recorded of the various steel packing cones and rings and the carboloy closure block and a wrapping of copper foil. The latter was always interposed as a precaution, perhaps unnecessarily, against rupture of the steel containing vessel by alloying between lead and steel at these high pressures. The weights of all the contents of the pressure vessel obviously affect the total compression and corrections were calculated for slight variations in the amount of steel etc. from run to run; these corrections were usually negligible.

At 50,000 kg/cm^2 the volume of the liquids of this paper is on the average about 0.6 of the initial volume; it is evident therefore that the walls of the capsule are subject to and must withstand heavy distortions. The distortion is so great that only a few applications of pressure to the capsule are possible. After considerable experience the routine was adopted of not attempting more than two applications of pressure, after which the apparatus was taken down and set up again with a new filling. The usual form of the distortion of the capsule is a thickening of the top, and thinning and eventual necking down and leak at the bottom part. The precise manner of deformation is sensitive to slight changes in the shape of the capsule; a comparatively slight change from the shape indicated in Figure 1 results in necking down near the top instead of at the bottom. The precise manner of distortion is also determined by the absolute compression of the contents of the capsule.

The use of lead as the material of the capsule, instead of the more easily deformable indium which was used in the previous work, was necessitated by the fact that the temperature range contemplated was above the melting temperature of indium. In the former work measurements were made at room temperature and −80° C.; in this work the temperature ranges upward from room temperature usually to 175° but on one occasion to 225°. No measurements were attempted below room temperature; for one thing the greater stiffness of the lead would have introduced error. Temperature control was by an electrically heated, regulated, and stirred oil bath, in the same container that was used for the dry ice in the previous work. At temperatures above 100° the steel pressure vessels are materially weakened; at least one particular kind of rupture is much more frequent, namely across the threads at the closure end. I had originally been troubled by this same sort of rupture at room temperature on first beginning work with the apparatus for 50,000, and avoided it by changing the external angle of the containers. No further change in this direction is now feasible, however, and after attempting a number of different devices I have come to accept this as a necessary limitation of the present design. The result is that in the following compressions above 100° are given to a maximum pressure of only 45,000 instead of 50,000. Even with this reduction, ruptures at the higher temperatures have been discouragingly frequent, and account for the fact that a number of compressions in the following are not given over the full temperature range

The method is, as before, differential. Piston displacement is measured as a function of pressure when the vessel is filled with capsule an liquid, and then a comparison run is made wit the capsule replaced by a known amount o steel and an equal amount of lead. The difference of displacement of the two runs is taken.

The distortion of the vessel approximately cancels from this difference, leaving the difference of compression of steel and liquid. In the following my new results for the compression of steel up to 30,000 were used,[4] extrapolating from 30,000 to 50,000, which should make no appreciable error in view of the small compressibility of steel compared with that of the various liquids. The compression of lead also enters the results as a small correction, because it was usually not possible to use exactly the same amount of lead in the two runs. The values for the compression of lead used in this correction were obtained from unpublished results also up to 30,000, and extrapolated by Murnaghan's formula[5] to 50,000. The values assumed for $\Delta V/V_0$ of lead were: at 25° 0.051 and 0.091 at 25,000 and 50,000 respectively; at 75° 0.052 and 0.092 at the same pressures, and at 125° and 175° the values given by linear extrapolation from 25° and 75°.

The calculations were made by the same formulas as in the preceding work.

The melting parameters and the compressions were determined in two independent sets of experiments. The necessity for this arose from the fact that measurements of compression demand operation on a definite time schedule in order that the distortions connected with hysteresis and similar effects may be reproducible, whereas the freezing measurements cannot be conducted on a fixed time schedule because the lag in the appearance of the solid phase and the velocity of crystallization to the solid after its nucleus has been formed vary greatly from substance to substance. It is fortunate in view of this that hysteresis produces no essential error in the determination of the freezing parameters.

As in all my earlier work, the freezing parameters which were measured were equilibrium pressure and temperature and the corresponding change of volume. At each temperature two values of the change of volume were obtained, with increasing and decreasing pressure; the average of these was usually taken. The latent heats etc. are then calculated by an application of Clapeyron's equation. All the determinations were made by isothermal variation of pressure; the method of variation of temperature at constant volume which has been used in some of my work was not well adapted to the apparatus and was not used. In general the melting parameters were determined at 25° intervals. Pressure was not varied over the entire range, but by only so much on each side of the equilibrium pressure that the reactions had surely run to completion and the full width of the frictional hysteresis loop due to reversal of direction of change of pressure attained. Pressure was varied in steps of 400 kg/cm^2 instead of the steps of 2,000 used in measuring compressions. The regular time schedule was used when the reaction from one phase to the other was not running; when the reaction was running, however, it was customary to wait after each change of pressure until the reaction had approximately ceased. The melting pressure on any isotherm was taken from the readings with decreasing pressure, since the solid phase does not superheat, whereas the liquid phase almost always subcools. The equilibrium pressure was taken as the mean of the last pressure before melting starts and the first pressure after melting just begins, as shown by the change of volume, corrected by one half the width of the frictional hysteresis loop above and below the melting. Since the pressure steps are 400 kg/cm^2, the error in a single melting pressure thus determined should not be more than 200 kg/cm^2.

Subcooling of the liquid becomes an increasingly prominent phenomenon at high pressures; the reluctance of the solid phase to appear constituted one of the major experimental difficulties of this work. In several cases the melting curves could not be carried to as high temperatures as it might appear they should, because pressures higher than 50,000 would have been required to induce the appearance of the solid phase. A phenomenon found by Tammann imposed a restriction on the manipulation, namely the ease of formation of a nucleus of the solid out of the liquid passes through a maximum with increasing pressure. This means that the solid cannot be induced to appear merely by raising pressure to the maximum beyond the equilibrium pressure and waiting, but if the solid will not appear within a practical time on increasing pressure to the most favorable value, there is nothing to be done. As a consequence of these various lag phenomena it was possible for one substance, ethyl acetate, to run two sets of compression curves, one for the metastable liquid in the domain of the solid up to the maximum pressure, and the other for the solid. For another substance, methyl cyclohexane, it was possible to get through the region of appreciable reaction velocity with sufficient speed to carry a large fraction of the material up to the maximum pressure in the form of the subcooled liquid and obtain measurements of its compression.

Compressions were measured at 50° intervals. It was the original intention to measure all compressions at 25° (room temperature), 75°, 125°, and 175°, but in view of the experimental difficulties already described, the two higher temperatures were dispensed with in six cases. All the compressions given in the following are the means obtained with two or more independent set-ups in different pressure vessels. In general, one set-up was used twice, at 25° and 75° or at 125° and 175°. The pressure vessels were calibrated by blank runs with iron at all four temperatures; the cases were distressingly numerous in which the vessel survived only the calibrating runs. Twenty four pressure vessels were used in the measurements of compression. Of these, four only were used for the measurements at 25° and 75° to a pressure maximum of 50,000, with an average life of 24.5 exposures to the maximum. Twenty vessels were used for the measurements at 125° and 175° to a maximum of 45,000, with an average life of 5.0 exposures.

The compressibility of liquids drops off very fast in the first few thousand atmospheres; the curves of piston displacement against pressure are initially very steep, rapidly flattening out. Error from friction is especially large at the lower end of the pressure range, where the curve is steep and the forces relatively small. As a consequence, I did not attempt to use the readings to give any results at pressures lower than 5,000, and the volume decrements given in the following are all calculated from 5,000 as the zero. For the compressions up to 5,000 it is necessary to rely on other work. For a number of the following substances these previous measurements have been made, but unfortunately there are a number which have not been previously measured, and for them the conversion of the present measurements into absolute volumes as a function of pressure must wait for future measurements. Not only are the values below 5,000 obtained by the present method too inaccurate, but something of the same inaccuracy also affects the measurements between 5,000 and 10,000. I have given the preference to the former values in the following, and have corrected the values of the present work at pressures higher than 10,000 by an additive term so chosen as to reduce the present results to agreement with the former ones in the interval 5,000 to 10,000. The magnitude of the correction so applied is given for the various substances in the following detailed description. In no case are there previous measurements between 5,000 and 10,000 at the two higher temperatures, 125° and 175°. At pressures above 5,000 the behavior of liquids is settling down to linearity with temperature, so that in a number of instances it seemed best to extrapolate the previous values for 25° and 75° up to 125° and 175° for the interval 5,000 to 10,000, and apply the additive correction so determined to the present measurements at 125° and 175°. The details are given in the following.

The accuracy of the results probably does not in general, although there may be a few exceptions, justify the retention of more than three significant figures, and this is all that are given in the following final results. All the results were calculated to four figures, however, and the averages of the two runs were subjected to a smoothing by graphical methods to give smooth first differences out to the fourth decimal place. The results given in the following were obtained by contraction of these four figure results. Any apparent lack of smoothness in the first differences arises from the play of the fourth figure. As a rough indication of the accuracy, the deviations of the individual runs from the mean at the maximum pressure are given, usually to the fourth figure. This deviation does not always tell the complete story, however, because the maximum percentage deviations are not always at the maximum pressure. It must also be considered that with so many substances there must be some for which the error in the final result is greater than indicated by the agreement between the individual measurements, and some for which the error is less than would be inferred from the divergence of the two measurements.

An additional indication of the accuracy is given by the smoothness of the figures *across* the columns of the tables, that is, by the smoothness with respect to temperature at constant pressure. In adjusting the results, smoothings were made with respect to pressure at the various constant temperatures. The only cross smoothings were occasionally at the lowest pressure, as already described. At the upper pressures of the range the different isotherms are therefore essentially independent, and the smoothness of the progression from column to column affords a check on the probable accuracy.

Not only were the compressions adjusted as described to agree with my previous values at the lower end of the pressure range, but they were also adjusted, for those substances which freeze, to be consistent with the values here found for the melting parameters, in particular for the change of volume. The experimental values for the change of volume on freezing always show some scatter; the values obtained during the compression measurements were not obtained by a procedure particularly well adapted to give good values for this particular parameter, and there is no question but that the values obtained with the other set-ups when the manipulation was particularly made to give the freezing parameters should be preferred. The adjustments thus demanded were not large, and it was not possible to devise any unique procedure for making them, but the procedure was varied according to the details of the behavior of the different substances. The uncertainty would be expected to be greatest in general in the volumes of the solid just beyond the freezing point, since freezing might not have been completed here because of subcooling or perhaps the effect of impurity. The rough general procedure was to retain without adjustment the values given directly by the readings for the liquid up to the freezing pressure, then at the freezing pressure to give the solid the volume demanded by the special determinations of the melting parameters, and then to distribute the alterations thus demanded in the measured compressions of the solid above the freezing pressure over the entire pressure range, tapering off linearly to zero adjustment at the top pressure. The numerical details are given in the following.

DETAILED PRESENTATION OF DATA

Methyl Alcohol. The material was specially purified by redistillation by Mr. L. D. Berger in the Chemical Laboratory of Harvard University. Compressions were measured at all four temperatures in four different pressure vessels; at the lower two temperatures with two independent set-ups, and at the two higher temperatures with three set-ups. At 25° the material froze on one of the two runs, and rough values of the freezing parameters at this temperature were obtained. However, the freezing was very sluggish, and on the other set-up the material was carried in the metastable liquid condition to the maximum pressure. As a consequence values were obtained at 25° for the compressions above the melting point of both liquid and solid phases. In view of the sluggishness of the freezing and the magnitude of the freezing pressure at 25°, 30,000, the special effort was not made that would have been necessary to obtain other points on the freezing curve at higher temperatures.

In order to bring the volume decrements between 5,000 and 10,000 into agreement with the previous values a subtractive correction of 0.0009 was applied to all readings at 25° and of 0.0020 to the readings at 75°. Subtractive corrections of 0.002 at 125° and 0.005 at 175° were applied to give a smoothly extrapolated isobar at 10,000, but these two corrections are obviously in some doubt. At 25° the compressions of the two runs before adjustment differed at the maximum pressure by 4.6% from the mean and at 75° by 8.6%. At 125° the extreme deviation from the mean at the maximum pressure was 4.2% and at 175° 3.8%. These deviations are somewhat larger than the average. There was no particular consistency in the deviation from the mean given by any one pressure vessel.

TABLE I

METHYL ALCOHOL

ΔV, in cm³ per 0.792 gm. from 5,000 kg/cm² as zero

Pressure kg/cm²	ΔV				
	25°		75°	125°	175°
5,000	.000	(.819)	.000 (.838)	.000 (.859)	.000 (.881)
10,000	.062		.066	.073	.082
15,000	.099		.106	.117	.128
20,000	.125		.135	.149	.161
25,000	.145		.157	.174	.187
30,000	.161	.179*	.173	.194	.208
35,000	.173	.189	.187	.210	.226
40,000	.183	.198	.198	.223	.240
45,000	.191	.206	.208	.234	.253
50,000	.199	.215	.218		

* Solid phase in this column.

The compressions are shown in Table I; in the 25° column the compressions of both liquid and solid are given above the freezing point. The figures in parentheses in the 5,000 row are the total volumes at 5,000 as given by previous work.[6] By subtracting the tabulated volume decrements the volume itself may be obtained as a function of pressure and temperature. The plan was adopted of tabulating consistently the volume decrements instead of the volume because for a number of substances only the decrements are known.

Ethyl Alcohol. The material I owe to Professor F. G. Keyes of M. I. T. who had especially purified it for use as one of his standard liquids to give one of the temperature fixed points of low temperature thermometry by its freezing point. Obviously the purity has to be high for such a

TABLE II

ETHYL ALCOHOL

Freezing Parameters

Pressure kg/cm²	Temp. °C	Slope $d\tau/dp$	ΔV cm³/gm	Lat. Ht. kg cm/gm	$p\Delta V$ kg cm/gm	ΔE kg cm/gm	ΔS kg cm/gm°
0	−117°.3						
5,000	− 76.						
10,000	− 39.						
15,000	− 5.	.0064	.0443	1,850	660	1,190	6.93
20,000	+ 25.	.0059	.0435	2,200	870	1,330	7.38
25,000	54.	.0056	.0428	2,480	1,070	1,410	7.58
30,000	82.	.0055	.0420	2,700	1,260	1,440	7.60
35,000	109.	.0054	.0412	2,910	1,440	1,470	7.66

use. Compressions were measured at all four temperatures, with two independent set-ups at the two lower and three at the two upper temperatures, in four different pressure vessels. In addition, the freezing parameters were determined at four temperatures in two vessels; the maximum freezing temperature attempted was 100°, where the equilibrium pressure is 33,200 kg/cm². The increasing sluggishness of the reaction did not permit the determination of freezing parameters at higher temperatures.

In order to secure agreement with the previous measurements[7] an additive correction of 0.0050 was applied at 25° and of 0.0003 at 75°. The corresponding corrections, obtained by extrapolation, were 0.003 at 125° and 0.003 at 175°. In order to secure agreement with the independently measured freezing parameters further adjustments were made as explained; these were at the maximum 0.0020 at 25° and 0.0010 at 75°. The deviation from the mean at the maximum pressure of the compressions of the two independent runs was 0.3% at 25°, 1.8% at 75°, and the extreme deviation at the two higher temperatures from the means was 3.7% at 125° and 4.1% at 175°.

TABLE III

ETHYL ALCOHOL

ΔV, in cm³ per 0.789 gm, from 5,000 kg/cm² as zero

Pressure kg/cm²	ΔV			
	25°	75°	125°	175°
5,000	.000 (.819)	.000 (.836)	.000	.000
10,000	.063	.069	.071	.076
15,000	.100	.109	.113	.119
20.000	.128 .163*	.137	.144	.151
25.000	.181	.159	.168	.175
28,700		.174 .207*		
30,000	.196	.211	.187	.195
35,000	.209	.223	.203	.211
40,000	.220	.233	.217	.225
45,000	.230	.242	.230	.238
50.000	.238	.250		

* Solid below this.

The freezing parameters are given in Table II and Figure 2, and the compressions in Table III. Notice that the freezing parameters are given in terms of one gram of material and the compressions in terms of that amount of material which occupies one cubic centimeter at room temperature. This is the usual usage; following this usage means that one cannot pass directly from the volume discontinuities listed under the freezing parameters to the difference of compressions for liquid and solid listed in the tables of compressions, but one must multiply by the density. Notice also that the latent heats etc. are given in mechanical units instead of in calories as is often done; the mechanical units are given directly by Clapeyron's equation, and appear to be the most natural to use under the circumstances.

n-Propyl Alcohol. The material was purified by distillation by Mr. L. D. Berger, who reported the values: B. P. 96°.31 C at 760.3 mm. $n_D^{17.8}$ 1.3860. Compressions were measured at all four temperatures, with two independent set-ups at 25° and 75° and with three at 125° and 175° in five pressure vessels. The material did not freeze under pressure in the temperature range.

To secure agreement with previous results[8] in the pressure range 5,000 to 10,000 a subtractive correction of 0.0043 was applied to the results at 25° and of 0.0072 at 75°. No correction was applied at 125° or 175°, although an argument could be made for an additive correction of 0.002 at 175°. The divergence from the mean of the two independent runs at the maximum pressure was 1.1% at 25°, and 0.3% at 75°. The corresponding extreme deviations were 0.4% at 125° and 2.8% at 175°.

The compressions are given in Table IV.

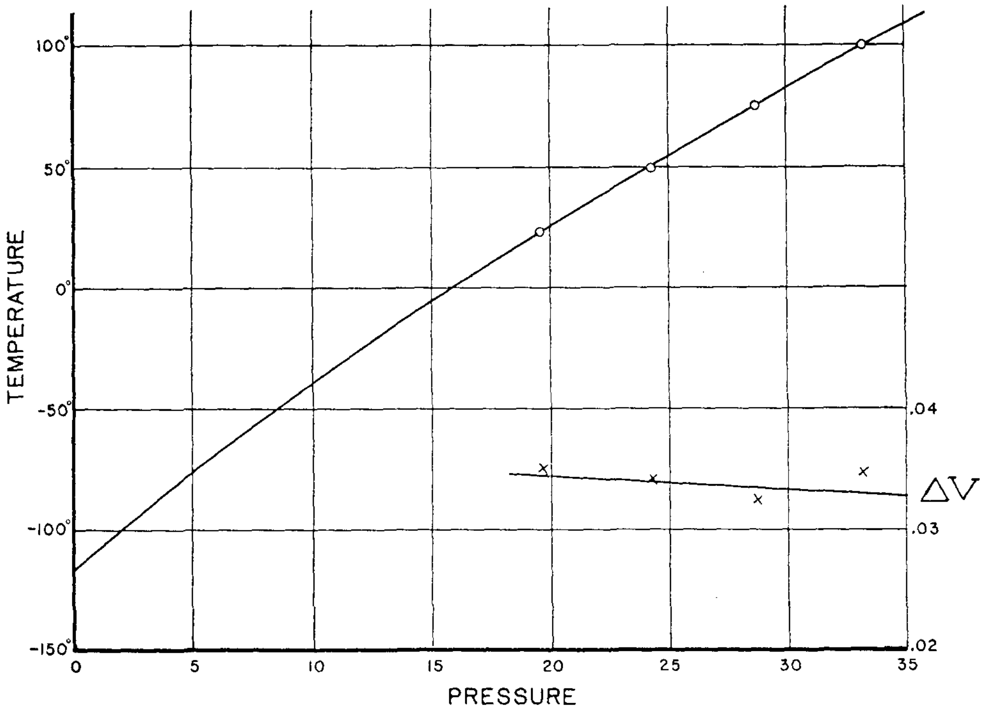

FIG. 2. The freezing parameters of ethyl alcohol. The freezing temperatures as a function of pressure are shown by the circles, with the scale to the left, and the *fractional* changes of volume by the crosses, with the scale to the right.

TABLE IV

n-PROPYL ALCOHOL

ΔV, in cm^3 per 0.804 gm, from 5,000 kg/cm^2 as zero.

Pressure kg/cm^2	ΔV			
	25°	75°	125^3	175°
5,000	.000 (.840)	.000 (.857)	.000	.000
10,000	.054	.058	.064	.068
15,000	.088	.096	.106	.114
20.000	.113	.122	.135	.144
25,000	.134	.143	.157	.168
30,000	.151	.160	.176	.187
35,000	.166	.174	.192	.203
40,000	.179	.187	.207	.217
45,000	.191	.199	.219	.229
50,000	.201	.210		

TABLE V

i-PROPYL ALCOHOL

ΔV, in cm^3 per 0.786 gm. from 5,000 kg/cm^2 as zero.

Pressure kg/cm^2	ΔV			
	25°	75°	125°	175°
5,000	.000 (.833)	.000 (.850)	.000	.000
10,000	.060	.065	.070	.075
15,000	.096	.104	.110	.120
20,000	.121	.131	.139	.150
25,000	.141	.152	.161	.174
30,000	.158	.170	.179	.193
35,000	.173	.185	.194	.208
40,000	.186	.197	.206	.220
45,000	.197	.208	.217	.231
50.000	.207	.217		

i-Propyl Alcohol. The material was obtained from Prof. Brunel many years ago. On redistillation it all boiled at 82°.7 except the very last at 82°.8. This material did not freeze in the temperature range of this work, so only the compressions were measured, at all four temperatures, with two independent set-ups at each temperature, and in four different pressure vessels.

The additive corrections were 0.0011, − 0.0014, 0.0017, and − 0.0021 at 25°, 75°, 125°, and 175° respectively. At 25° the deviations from the mean compression at the maximum pressure were 1.0%, at 75° 0.9%, at 125° 0.5%, and at 175° 1.2%.

The compressions are given in Table V. The material has been previously measured.[9]

n-Butyl Alcohol. The material was specially purified by distillation by Mr. L. D. Berger. Compressions were measured at all four temperatures: with two different set-ups and in two different pressure vessels at 25° and 75°, and with three set-ups and in three vessels at 125° and 175°. The freezing parameters were determined at 25° intervals from 25° to 150° in two different vessels with two different set-ups.

Because of the low freezing pressure, previous values[10] for the compression exist only at 75°. Here a subtractive correction of 0.0024 was applied. No attempt was made to estimate a probable correction at 25°, the value given by the unadjusted measurements appearing plausible enough. At 125° and 175° the additive corrections were .0009 and − .0017. At 25° the deviation of the two runs from the mean at the maximum pressure was 4.5%, at 75° 3.2%, at 125° 0.5%, and at 175° 0.8%. In order to secure agreement with the directly determined freezing parameters a further adjustment rising at its maximum to 0.0014 had to be applied at 75°; no such adjustment was necessary at 25°. The adjustment at 125° was .0009.

The freezing parameters are given in Table VI and Figure 3, and the compressions in Table VII.

TABLE VI

n-Butyl Alcohol

Freezing Parameters.

Pressure kg/cm²	Temp. °C.	Slope $d\tau/dp$	ΔV cm³/gm	Lat. Ht. kg cm/gm	$p\Delta V$ kg cm/gm	ΔE kg cm/gm	ΔS kg cm/gm°
0	− 89°.8						
5,000	− 33.						
10,000	+ 12.	.0080	.0478	1,690	480	1,210	5.97
15,000	49.	.0068	.0432	2,050	650	1,400	6.35
20,000	80	.0058	.0399	2,430	800	1,630	6.88
25,000	108	.0052	.0373	2,730	930	1,800	7.17
30,000	132	.0047	.0352	3,040	1,070	1,970	7.49
35,000	155	.0042	.0333	3,390	1,170	2,220	7.92

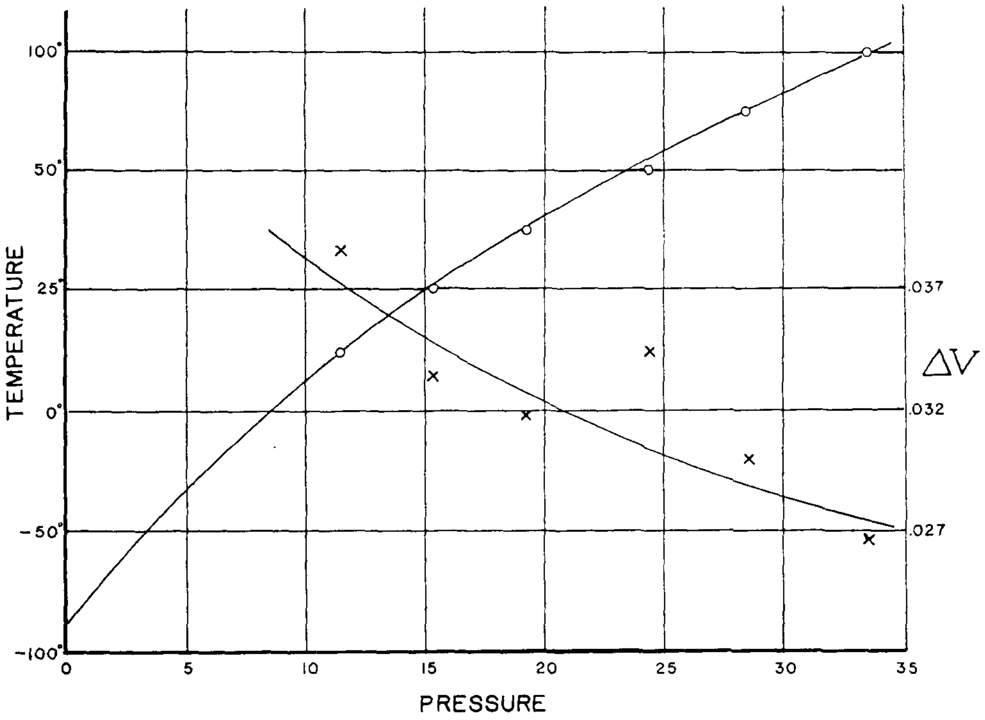

Fig. 3. The freezing parameters of n-butyl alcohol. The freezing temperatures as a function of pressure are shown by the circles, with the scale to the left, and the *fractional* changes of volume by the crosses, with the scale to the right.

TABLE VII

n-BUTYL ALCOHOL

ΔV, in cm³ per 0.810 gm, from 5,000 kg/cm² as zero

Pressure kg/cm²	ΔV 25°	ΔV 75°	ΔV 125°	ΔV 175°
5,000	.000 (.845)	.000 (.862)	.000	.000
10,000	.058	.063	.068	.074
11,700	.072 .109*			
15,000	.125	.100	.110	.119
19,000		.122 .155*		
20,000	.144	.159	.140	.150
25,000	.160	.178	.165	.174
27,000			.174 .203*	
30,000	.173	.192	.212	.194
35,000	.185	.204	.225	.210
40,000	.195	.214	.236	.224
45,000	.205	.223	.244	.235
50,000	.213	.231		

* Solid at higher pressures.

TABLE VIII

n-AMYL ALCOHOL

ΔV, cm³ per 0,817 gm, from 5,000 kg/cm² as zero

Pressure kg/cm²	ΔV 25°	ΔV 75°	ΔV 125°	ΔV 175°
5,000	.000 (.843)	.000 (.860)	.000	.000
10,000	.056	.061	.067	.073
15,000	.093	.100	.107	.115
20,000	.119	.127	.136	.146
25,000	.140	.149	.159	.170
30,000	.157	.167	.178	.189
35,000	.172	.183	.194	.205
40,000	.184	.196	.207	.219
45,000	.194	.207	.218	.230
50,000	.203	.217		

n-Amyl Alcohol. The material was obtained many years ago from Prof. J. Timmermans of the Bureau Belge d'Étalons Chimiques. Its constants have been described in a previous paper.[11] The material did not freeze in the range of this work. Compressions were measured at all four temperatures, with two different set-ups at each temperature, and in four different pressure vessels.

The additive corrections imposed by previous work[12] were 0.0024, − 0.0026, 0.0002, and − 0.0019 at 25°, 75°, 125°, and 175° respectively. The deviations of the independent runs from the means at the maximum pressure were 0.1%, 0.06%, 4.3%, and 1.1% at the four temperatures respectively.

The compressions are given in Table VIII.

Ethyl Bromide. The material was specially distilled by Mr. L. D. Berger. The freezing parameters were determined at three temperatures, 25°, 50°, and 75°, with a single set-up. More points on the freezing curve were not attempted because of the very great subcooling; at 75° the equilibrium pressure is 28,000, but it

TABLE IX

ETHYL BROMIDE

Freezing Parameters

Pressure kg/cm²	Temp. °C	Slope $d\tau/dp$	ΔV cm³/gm	Lat. Ht. kg cm/gm	$p\Delta V$ kg cm/gm	ΔE kg cm/gm	ΔS kg cm/gm°
0	−119°.						
5,000	− 70.						
10,000	− 29.						
15,000	+ 5	.0062	.0189	845	280	560	3.03
20,000	34	.0053	.0159	916	320	600	2.98
25,000	58	.0045	.0133	975	340	630	2.94
30,000	80	.0039	.0110	996	330	670	2.81

TABLE X

ETHYL BROMIDE

ΔV, cm³ per 1.430 gm, from 5.000 kg/cm² as zero.

Pressure kg/cm²	ΔV 25°	ΔV 75°	ΔV 125°	ΔV 175°
5,000	.000 (.814)	.000 (.823)	.000	.000
10,000	.061	.066	.071	.076
15,000	.099	.104	.116	.122
18,400	.120 .144*			
20,000	.151	.130	.147	.154
25,000	.171	.152	.171	.178
28,500		.167 .184*		
30,000	.188	.189	.191	.198
35,000	.201	.203	.206	.213
40,000	.212	.214	.218	.226
45,000	.222	.223	.229	.237
50,000	.230	.231		

* Solid below this.

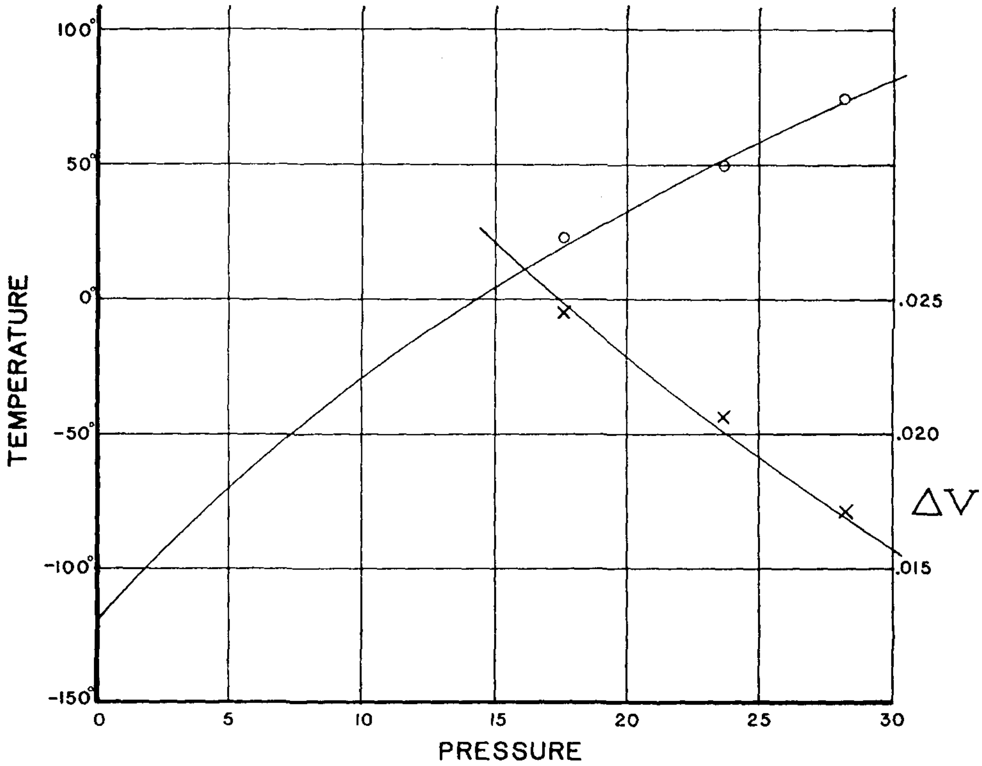

FIG. 4. The freezing parameters of ethyl bromide. The freezing temperatures as a function of pressure are shown by the circles, with the scale to the left, and the *proportional* changes of volume by the crosses, with the scale to the right.

TABLE XI

n-PROPYL BROMIDE

Freezing Parameters

Pressure kg/cm²	Temp. °C	Slope $d\tau/dp$	ΔV cm³/gm	Lat. Ht. kg cm/gm	$p\Delta V$ kg cm/gm	ΔE kg cm/gm	ΔS kg cm/gm°
0	−110°						
5,000	− 56						
10,000	− 8						
15,000	+ 34	.0079	.0229	890	340	550	2.90
20,000	71	.0072	.0197	940	390	550	2.74
25,000	105	.0067	.0174	990	440	540	2.61
30,000	138	.0062	.0157	1,040	470	570	2.52
35,000	169	.0059	.0143	1,070	500	570	2.42
40,000	197	.0056	.0131	1,090	520	570	2.32

required the application of 45,000 to induce freezing to begin. Compressions were measured at all four temperatures, with two different set-ups and in two different pressure vessels at 25°, 75° and 175°, and in three different pressure vessels at 125°. The additive corrections necessary to secure agreement with previous work[13] were 0.0021 at 25°, 0.0026 at 75°, − 0.0028 at 125°, and − 0.0070 at 175°. In order to secure agreement between the compression runs and the determinations of freezing parameters an additional distributed adjustment rising to the maximum of 0.0043 at 25° and 0.0016 at 75° was applied. The deviations from the mean at the maximum pressure were 2.6% at 25°, 3.2% at 75°, 0.5% at 125°, and 0.7% at 175°.

The freezing parameters are given in Table IX and Figure 4 and the compressions in Table X.

n-Propyl Bromide. The material was redistilled by Mr. L. D. Berger who reported: B. P. 71°.5 at

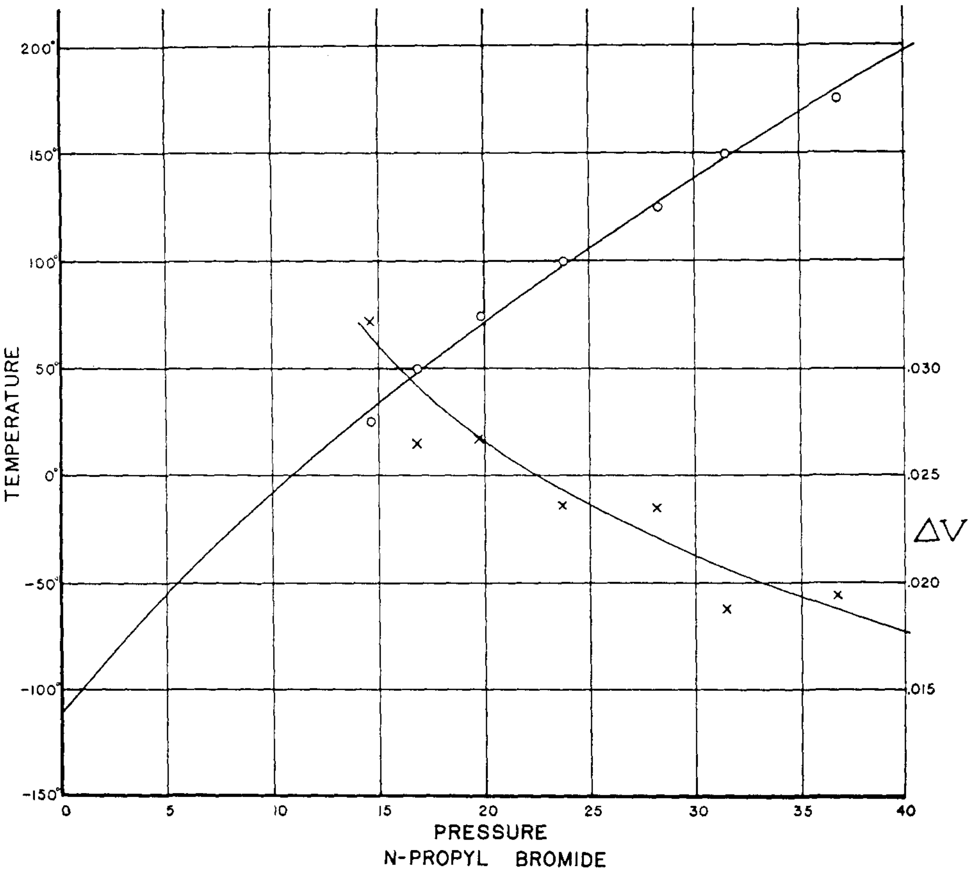

FIG. 5. The freezing parameters of n-propyl bromide. The freezing temperatures as a function of pressure are shown by the circles, with the scale to the left, and the *fractional* changes of volume by the crosses, with the scale to the right.

760 mm. n_D^{18} 1.4341. Compressions were measured at the four temperatures, with two different set-ups at each temperature and in four different pressure vessels. The freezing parameters were determined at 25° intervals from 25° to 175° with three different set-ups and in three different pressure vessels.

The additive corrections applied to secure agreement with the previous compressions[14] between 5,000 and 10,000 were 0.0036 at 25° and 0.0007 at 75°. To secure agreement with the independently measured freezing parameters additional corrections of a maximum of 0.0034 at 25°, 0.0006 at 75°, and .0023 at 125° were applied. The deviation from the mean at the maximum pressure was 1.8% at 25°, 1.8% also at 75°, 2.9% at 125°, and 0.0 at 175°.

The freezing parameters are shown in Table XI and Figure 5, and the compressions in Table XII.

TABLE XII

n-PROPYL BROMIDE

ΔV, cm³ per 1.353 gm. from 5,000 kg/cm² as zero

Pressure kg/cm²	ΔV			
	25°	75°	125°	175°
5,000	.000 (.824)	.000 (.843)	.000	.000
10,000	.062	.067	.072	.077
14,000	.093 .125*			
15,000	.131	.106	.114	.119
20,000	.154	.136	.143	.149
20,600		.140 .166*		
25,000	.171	.182	.166	.173
28,000			.178 .200*	
30,000	.184	.196	.207	.193
35,000	.193	.206	.219	.208
40,000	.202	.215	.231	.221
45,000	.209	.222	.241	.234
50,000	.216	.228		

* Solid at higher pressures.

n-Butyl Bromide. The material was prepared by distillation by Mr. L. D. Berger. Compressions were measured at 25° and 75°; it does not freeze in the present range.

An additive correction of 0.0034 was applied at 25° and of 0.0013 at 75° to secure agreement with previous work.[15] The deviations from the means at the maximum pressure were 0.1% at 25° and 1.5% at 75°.

The compressions are given in Table XIII.

TABLE XIII

n-Butyl Bromide

ΔV, cm³ per 1.275 gm, from 5,000 kg/cm² as zero

Pressure kg/cm²	ΔV 25°	ΔV 75°
5,000	.000 (.826)	.000 (.844)
10,000	.062	.067
15,000	.098	.105
20,000	.125	.133
25,000	.148	.155
30,000	.166	.173
35,000	.182	.189
40,000	.195	.202
45,000	.207	.214
50,000	.218	.224

Ethyl Acetate. The material was from Timmermans.[11] Runs were made at all four temperatures; at 25° and 75° with four set-ups and in four different pressure vessels, and at 125° and 175° with three set-ups and in three vessels. The material freezes very sluggishly. If the normal time schedule of pressure increments of 2,000 at two minute intervals is adhered to, freezing does not occur at all with increasing pressure, but the subcooled liquid is carried up to the maximum pressure. On release of pressure, however, freezing occurs on sufficiently close approach to the melting point. This has a paradoxical appearance, for a phase change which runs with decreasing volume is initiated by a decrease of pressure. The paradox consists in the apparent contradiction with the requirement of thermodynamics that the phase stable at the lower pressure have the larger volume. A moment's consideration shows, however, that the paradox is only superficial. The freezing on decreasing pressure occurs so close to the equilibrium point that it is easy to smooth across the bulge thereby produced on the decreasing curve, thus obtaining the normal increasing and decreasing curves for the liquid over the entire range, from which the compression of the liquid up to the maximum pressure can be obtained in the regular way. On the other hand the solid can be induced to appear if one delays a suitable time in the neighborhood of the freezing point with increasing pressure, and in this way the compressions of the stable phases, liquid below melting pressure and solid above, may be obtained in the regular way. Of the four sets of runs at 25° and 75°, two were so manipulated as to give the liquid over the entire range and the other two so as to give liquid and solid in their regions of stability. At 125° freezing was encountered on two of the three runs, so that these runs give the compression of the solid in the upper part of the range. On the third run at 125° the substance remained liquid over the entire range. No freezing occurred during any of the three runs at 175°.

There are no previous measurements on this material, so the usual additive corrections could not be applied. The low pressure values appear reasonable without correction. The deviations from the mean of the compressions of the subcooled liquid were at the maximum pressure 2.0% and 4.3% at 25° and 75° respectively; the corresponding deviations for the solid were 0.5% and 1.1%.

The compressions of the solid and liquid phases are given in Table XIV. The freezing parameters at 25° and 75° may be taken from this table. These parameters are probably not as accurate as those for other materials determined by manipulations made for the express purpose; in particular the very small drop in the volume contraction

TABLE XIV

Ethyl Acetate

ΔV, in cm³ per 0.899 gm, from 5,000 kg/cm² as zero

Pressure kg/cm²	ΔV 25°		ΔV 75°		ΔV 125°		ΔV 175°
5,000	.000		.000		.000		.000
10,000	.059		.066		.069		.074
12,100	.076	.107*					
15,000	.095	.122	.105		.111		.118
20,000	.122	.143	.134		.141		.149
23,800			.151	.181*			
25,000	.144	.161	.157	.185	.165		.172
30,000	.160	.176	.174	.200	.184		.191
31,860					.190	.213*	
35,000	.174	.188	.189	.211	.200	.220	.208
40,000	.185	.198	.201	.220	.214	.230	.220
45,000	.195	.207	.211	.227	.225	.239	.233
50,000	.203	.215	.220	.234			

* Solid in this column.

on freezing on passing from 25° to 75° is suspicious.

n-Amyl Ether. The material was obtained many years ago from Timmermans under the name "n-amyl oxide," one of his standard liquids.[11] It has been kept sealed in glass in the dark.

Runs were made with two set-ups and two pressure vessels at both 25° and 75°. Freezing occurs at a low pressure, so that most of the compressions are for the solid phase. The freezing parameters were determined only incidentally during the measurement of the compressions, without using small pressure steps or deviating from the regular time schedule. The freezing parameters implicitly contained in the table of compressions are therefore probably not as accurate as usual. In particular, the large drop in the change of volume on freezing on passing from 25° to 75° is suspicious.

There are no previous measurements for comparison at the low pressures. The deviation of the two runs from the mean at the maximum pressure was 1.4% at 25° and also 1.4% at 75°.

TABLE XV

n-Amyl ether

ΔV, cm³ per 0.774 gm, from 5,000 kg/cm² as zero

Pressure kg/cm²	ΔV	
	25°	75°
5,000	.000	.000
7,500	.031 .078*	
10,000	.094	.063
15,000	.119	.101 .130*
20,000	.140	.152
25,000	.158	.170
30,000	.173	.184
35,000	.186	.196
40,000	.197	.207
45,000	.207	.217
50,000	.217	.227

* Solid below this.

The compressions are shown in Table XV.

Chloroform. The material was from Prof. F. G. Keyes at M. I. T.

Compressions were measured at all four temperatures with two different set-ups at each temperature and in five pressure vessels. The freezing parameters were determined at nine temperatures, at 25° intervals from 25° to 225°, with four different set-ups, all in the same pressure vessel. Freezing is sharp and the manipulations easily made. The measurements were limited by the rapid rise of the melting curve and the attendant high temperatures rather than by the high pressures. On three occasions, at 100°, 175°, and 200°, clean cut anomalous results were obtained, for which the natural explanation is the existence of another form of the solid. It appears that when the liquid is carried beyond its normal melting curve the subcooled liquid may freeze to a new form of the solid, with a volume decrement only about two thirds of that when freezing to the normal form. This new form of the solid appears to be absolutely unstable with respect to the normal form over the entire range of these measurements, for no reversible transitions were found, but after a longer or shorter interval it flops irreversibly to the normal solid with the outstanding remaining one third of the volume decrement. The identity of the solid to which the unstable form flops is established as the normal solid because it exhibits normal melting on release of pressure.

There are no previous measurements for comparison. At 25° the melting pressure is so low that there is much uncertainty as to what the true compression of the liquid is at the freezing pressure, 6,200 kg/cm²; as far as these measurements go, the entire curve at 25° might be raised or lowered by a small constant amount. At 25° the

TABLE XVI

Chloroform

Freezing Parameters

Pressure kg/cm²	Temp. °C	Slope $d\tau/dp$	ΔV cm³/gm	Lat. Ht. kg cm/gm	$p\Delta V$ kg cm/gm	ΔE kg cm/gm	ΔS kg cm/gm°
0	− 63°.5	.0154					
5,000	+ 10.	.0140	.0430	870	220	650	3.07
10,000	76.	.0126	.0354	980	350	630	2.81
15,000	137.	.0116	.0301	1,070	450	620	2.59
20,000	192.	.0106	.0262	1,160	520	630	2.47
25,000	243	.0096	.0231	1,240	580	660	2.40

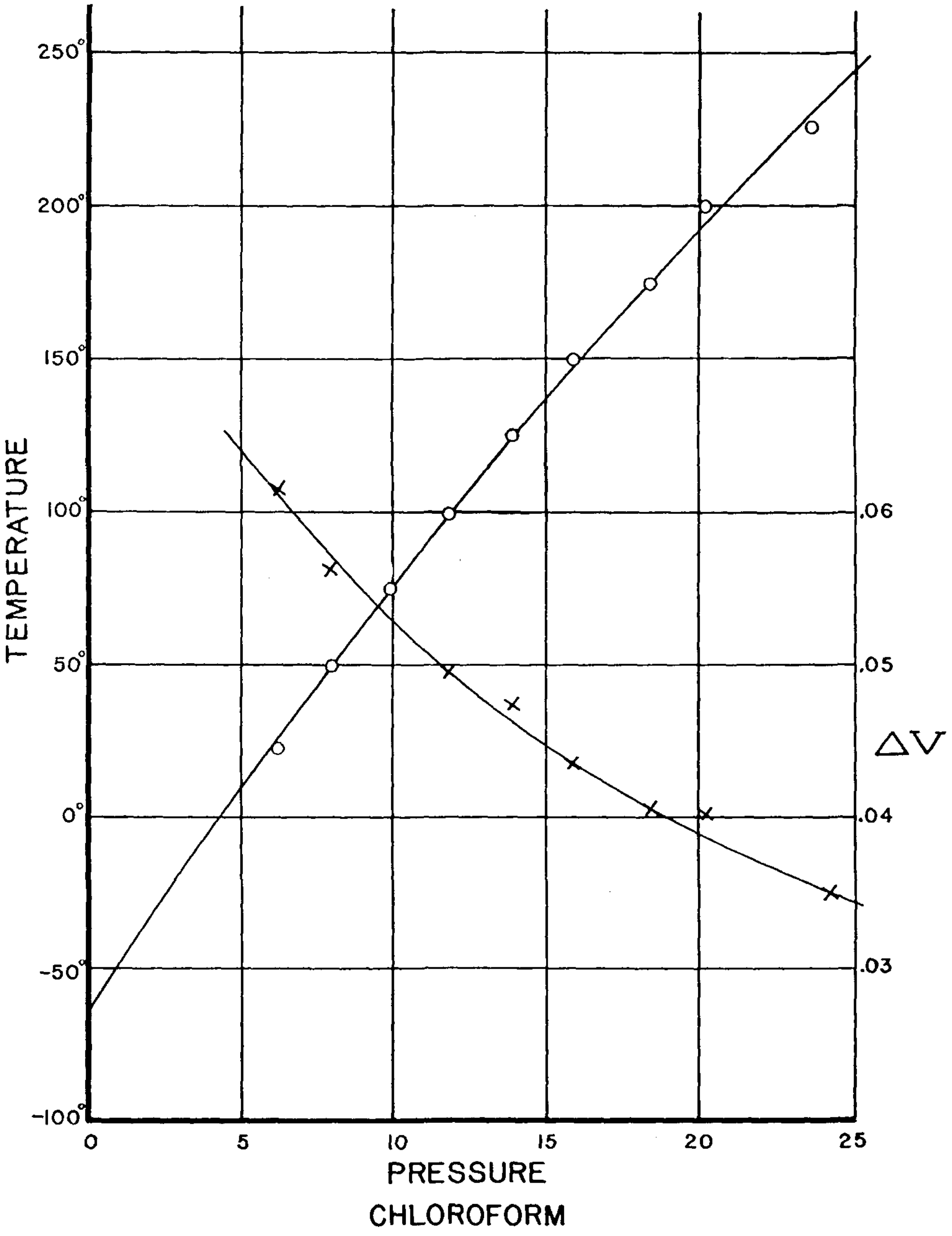

Fig. 6. The freezing parameters of chloroform. The freezing temperatures are shown by the circles, with the scale to the left, and the *fractional* changes of volume by the crosses, with the scale to the right.

deviation of the two runs from the mean at the maximum pressure was 0.5%, at 75° 4.4%, at 125° 0.7%, and at 175° 0.3%. The adjustments necessary to secure agreement between the compressions and the freezing parameters were unimportant except at 175°, where a maximum adjustment of − .0029 was applied.

The freezing parameters are shown in Table XVI and Figure 6, and the compressions in Table XVII.

Carbon Bisulfide. The material I owe to Professor F. G. Keyes of M. I. T. who had prepared it as one of his standard liquids for fixed points for low temperature thermometry.

The compressions were measured at all four temperatures with two set-ups at each temperature and in four pressure vessels. The freezing parameters were measured at 25° intervals from 25° to 175° with four set-ups, all in the same pressure vessel.

To secure agreement with previous results[16] between 5,000 and 10,000 additive corrections of 0.0036 and − 0.0077 were applied at 25° and 75° respectively; these corrections are somewhat larger than usual. To secure agreement between measurements of compression and the freezing parameters, a maximum adjustment of 0.0017 was made at 25°, of 0.0000 at 75°, of .0010 at 125°, and of .0014 at 175°. The deviations at the maximum pressure of the two independent runs from the mean were 1.4% at 25°, 0.3% at 75°, 1.7% at 125°, and 2.3% at 175°.

The freezing parameters are shown in Table XVIII and Figure 7, and the compressions in Table XIX.

TABLE XVII

Chloroform

ΔV, cm³ per 1.489 gm, from 5,000 kg/cm² as zero

Pressure kg/cm²	ΔV 25°	75°	125°	175°
5,000	.000	.000	.000	.000
6,200	.016 .077 *			
10,000	.104	.067 .119 *	.073	.079
14,000			.109 .155 *	
15,000	.130	.148	.161	.124
18,400				.148 .189 *
20,000	.150	.169	.185	.196
25,000	.167	.187	.203	.216
30,000	.181	.201	.218	.232
35,000	.194	.212	.230	.246
40,000	.204	.222	.241	.257
45,000	.213	.230	.250	.267
50,000	.221	.238		

* Solid at higher pressure.

TABLE XVIII

Carbon Bisulfide

Freezing Parameters

Pressure kg/cm²	Temp. °C	Slope $d\tau/dp$	ΔV cm³/gm	Lat. Ht. kg cm/gm	$p\Delta V$ kg cm/gm	ΔE kg cm/gm	ΔS kg cm/gm°
0	−111°.6						
5,000	− 51.						
10,000	0	.0095	.0285	820	290	540	3.00
15,000	+ 46.	.0088	.0247	900	370	530	2.80
20,000	89.	.0084	.0222	960	440	510	2.64
25,000	130.	.0080	.0205	1,030	510	520	2.56
30,000	170.	.0078	.0195	1,110	590	520	2.50
35,000	209.	.0076	.0187	1,190	650	530	2.46

In addition to the normal reversible freezing investigated above, carbon bisulfide has near the extreme edge of the attainable range a highly unusual irreversible change. This has already been described,[17] but for completeness will be mentioned again here. At temperatures of 175° or over and at pressures above 45,000, carbon bisulfide is transformed slowly and irreversibly into a black solid, permanent under atmospheric conditions, and by all the obvious tests a new form of CS_2. The density is about 4% greater than that of a mechanical mixture of the constituent elements. It has been suggested that it is a compound analogous to SiO_2; the structure, however, is too fine to check this suggestion by X-ray analysis.

Benzene, C_6H_6. The material was old stock from Timmermans,[11] kept sealed in glass.

Compressions were measured at 25° and 75° with two set-ups at each temperature and with two pressure vessels. At these temperatures the freezing pressures are so low as to be quite outside the range of this work, so that the compression measurements are on the solid phase. There is a previously known[18] transition line running nearly vertically at approximately 12,500; the compression measurements therefore embrace the transition and for the most part are concerned with the high pressure modification of the solid.

There are no previous measurements of compression for comparison, and no correction was attempted at low pressures. The results are given in Table XX. The initial compression between 5,000 and 10,000 at 75° seems improbably higher than that at 25°, and probably all the results tabulated at 75° should be adjusted by an

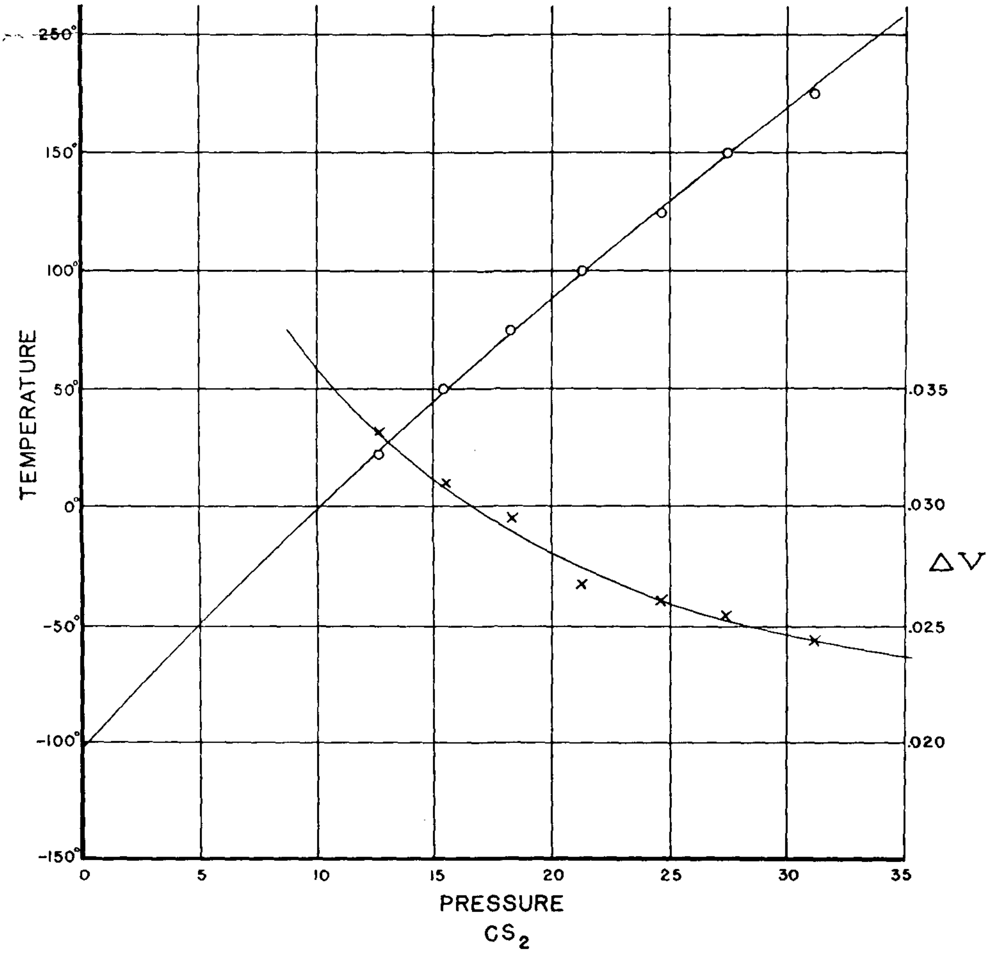

FIG. 7. The freezing parameters of carbon bisulfide. The freezing temperatures are shown by the circles, with the scale to the left, and the *fractional* changes of volume by the crosses, with the scale to the right.

additive constant of perhaps − 0.009. The volume change at the transition has been previously determined to be 0.0090 cm^3/gm, against 0.0061 given by the unadjusted measurements. Since this transition occurs at the lower pressure end of the range the previous value is doubtless to be preferred. A correction was therefore applied to bring agreement; this correction is a maximum of 0.0025 at 12,500 tapering off linearly to zero at 50,000. The two runs differed from the mean at the maximum pressure by 3.0% at 25° and 3.9% at 75°.

Chlorobenzene. The material I owe to Professor F. G. Keyes, being one of his standard liquids. Compressions were measured at all four temperatures with two set-ups at each temperature and in four pressure vessels. Freezing determinations were made at 25° intervals up to 200°, with six different set-ups in three different pressure vessels, giving, counting repetitions at the same temperature, fifteen determinations of the parameters. The large number of measurements of freezing was made necessary by the complexity of the phenomena. Chlorobenzene has a second modification of the solid, which replaces the ordinary form as the absolutely stable form at the higher temperatures. At the lower temperatures there is a strong tendency for the liquid not to freeze to the ordinary solid on passing beyond the normal melting line, but to freeze instead to the new form when the unstable prolongation of the melting line of the new form is reached. The solid thus formed by preference from the liquid is unstable with respect to the normal form, and it is a matter of caprice when and if at all it will flop irreversibly to the ordinary stable form. The

TABLE XIX

CARBON BISULFIDE

ΔV, cm³ per 1.261 gm, from 5,000 kg/cm² as zero

Pressure kg/cm²	ΔV 25°	75°	125°	175°
5,000	.000 (.827)	.000 (.845)	.000	.000
10,000	.063	.068	.073	.078
12,600	.086 .119 *			
15,000	.132	.110	.118	.126
18,300		.131 .160 *		
20,000	.155		.148	.159
24,400			.170 .196 *	
25,000	.174	.187	.196	.184
30,000	.190	.204	.218	.204
30,700				.206 .231 *
35,000	.204	.217	.231	.243
40,000	.215	.229	.242	.255
45,000	.225	.239	.250	.265
50,000	.233	.248		

* Solid at higher pressures.

TABLE XX

BENZENE

ΔV, cm³ per 0.878 gm, from 5,000 kg/cm² as zero

Pressure kg/cm²	ΔV 25°	75°
5,000	.000	.000
10,000	.036	.046
12,500	.049 .057 *	.061 .067 *
15,000	.068	.079
20,000	.088	.099
25,000	.105	.116
30,000	.119	.131
35,000	.131	.143
40,000	.141	.153
45,000	.150	.162
50,000	.158	.170

* Solid II below this, solid I above.

appearances and floppings of the unstable form were unpredictable, and increased the difficulty of getting complete or even understandable data. The new form might appear in its region of instability at temperatures as low as 25°. At 75° and above the preference for the new form was so great that no points on the melting curve of the ordinary modification could be obtained in spite of the fact that thermodynamically it is the stable form, so that no good evidence could be obtained as to the exact location of the reversible triple point between two solids and liquid or of the transition line between the two solids.

There are previous measurements[19] by which the low pressure compressions may be corrected only at 75°, the freezing pressure being too low at 25°. An additive correction of 0.0079 was applied at 75°. At 25° the two runs differed from the mean by 1.0% at the maximum pressure, at 75° by 2.3%, at 125° by 2.8%, and at 175° by 2.4%. At 75° the maximum adjustment necessary to make the compression results consistent with those for freezing parameters was 0.0053, at 125° 0.0002, and at 175° 0.0030. At 25° no adjustment was attempted of the compression of the solid at 10,000. At 25° the equilibrium pressure is 5,000; the compression listed for the solid at this pressure is merely the change of volume on melting as given by the freezing determinations. It is probable that the compression of the solid given in the table at 25° between 5,000 and 10,000 (0.034 = 0.079 − 0.045) is too high.

The freezing parameters are given in Table XXI and Figure 8 and the compressions in Table XXII.

Methylene Chloride. The material was prepared by distillation by Mr. L. D. Berger.

Compressions were measured at all four tem-

TABLE XXI

CHLOROBENZENE

Freezing Parameters

Pressure kg/cm²	Temp. °C	Slope $d\tau/dp$	ΔV cm³/gm	Lat. Ht. kg cm/gm	$p\Delta V$ kg cm/gm	ΔE kg cm/gm	ΔS kg cm/gm°
Liquid—I							
0	− 45°.2						
5,000	+ 25.	.0164	.0402	730	200	530	2.47
10,000	80	.0124					
Liquid—II							
10,000	30	.0159	.0388	740	390	350	2.44
15,000	103	.0134	.0331	930	500	430	2.47
20,000	166	.0118	.0296	1,100	590	510	2.51
25,000	222	.0107	.0280	1,290	700	590	2.61

TABLE XXII

CHLOROBENZENE

ΔV, cm³ per 1.107 gm. from 5,000 kg/cm² as zero

Pressure kg/cm²	ΔV			
	25°	75°	125°	175°
5,000	.000 .045 }*	.000 (.883)	.000	.000
10,000	.079	.058	.065	.071
13,000		.083 .122 }†		
15,000	.103	.133	.106	.111
16,700			.117 .152 }†	
20,000	.123	.156	.167	.140
20,800				.144 .176 }†
25,000	.140	.172	.183	.191
30,000	.154	.186	.197	.205
35,000	.166	.198	.208	.217
40,000	.177	.208	.218	.228
45,000	.186	.216	.226	.237
50,000	.194	.223		

* Solid I at higher pressures.

† Solid II at higher pressures.

peratures, with two different set-ups at each temperature and in five different pressure vessels. The freezing parameters were measured at 25° intervals from 25° to 150° with four different set-ups in three pressure vessels.

There are no previous measurements by which to correct the low pressure compressions.

At 25° the two independent compressions differed from the mean at the maximum pressure by 1.3%, at 75° by 3.4%, at 125° by 0.4%, and at 175° by 0.04%. An additional adjustment to bring the compressions into agreement with the melting parameters of 0.0031 at the maximum was applied at 25°, of 0.0011 at 75°, of .0030 at 125°, and of .0032 at 175°.

The melting parameters are given in Table XXIII and Figure 9 and the compressions in Table XXIV.

Ethylene Bromide. The material was from Timmermans.[11]

TABLE XXIII

METHYLENE CHLORIDE

Freezing Parameters

Pressure kg/cm²	Temp. °C	Slope $d\tau/dp$	ΔV cm³/gm	Lat. Ht. kg cm/gm	$p\Delta V$ kg cm/gm	ΔE kg cm/gm	ΔS kg cm/gm°
0	− 96°.7						
5,000	− 46						
10,000	0	.0088	.0338	1,050	340	710	3.86
15,000	+ 42	.0082	.0310	1,190	470	730	3.79
20,000	82	.0078	.0287	1,310	570	740	3.69
25,000	120	.0075	.0271	1,430	680	750	3.63
30,000	157	.0072	.0257	1,530	770	760	3.56

TABLE XXIV

METHYLENE CHLORIDE

ΔV, cm³ per 1.336 gm, from 5,000 kg/cm² as zero

Pressure kg/cm²	ΔV			
	25°	75°	125°	175°
5,000	.000	.000	.000	.000
10,000	.064	.069	.075	.081
13,000	.091 .134 }*			
15,000	.144	.110	.116	.127
19,000		.134 .173 }*		
20,000	.166	.176	.148	.159
25,000	.184	.198	.172	.185
25,700			.175 .211 }*	
30,000	.198	.213	.228	.205
32,600				.214 .247 }*
35,000	.210	.224	.239	.253
40,000	.219	.233	.248	.263
45,000	.228	.240	.256	.272
50,000	.235	.246		

* Solid at higher pressures.

TABLE XXV

ETHYLENE BROMIDE

ΔV, cm³ per 2.182 gm, from 5,000 kg/cm² as zero

Pressure kg/cm²	ΔV	
	25°	75°
5,000	.000	.000
10,000	.040	.045
15,000	.068	.075
20,000	.090	.097
25,000	.108	.114
30,000	.122	.129
35,000	.135	.142
40,000	.145	.152
45,000	.155	.162
50,000	.163	.171

The compressions were measured at 25° and 75° with two different set-ups at each temperature and in two pressure vessels.

There are no previous values for check at low pressures. The deviation of the independent runs from the mean at the maximum pressure was 0.2% at 25° and 1.8% at 75°.

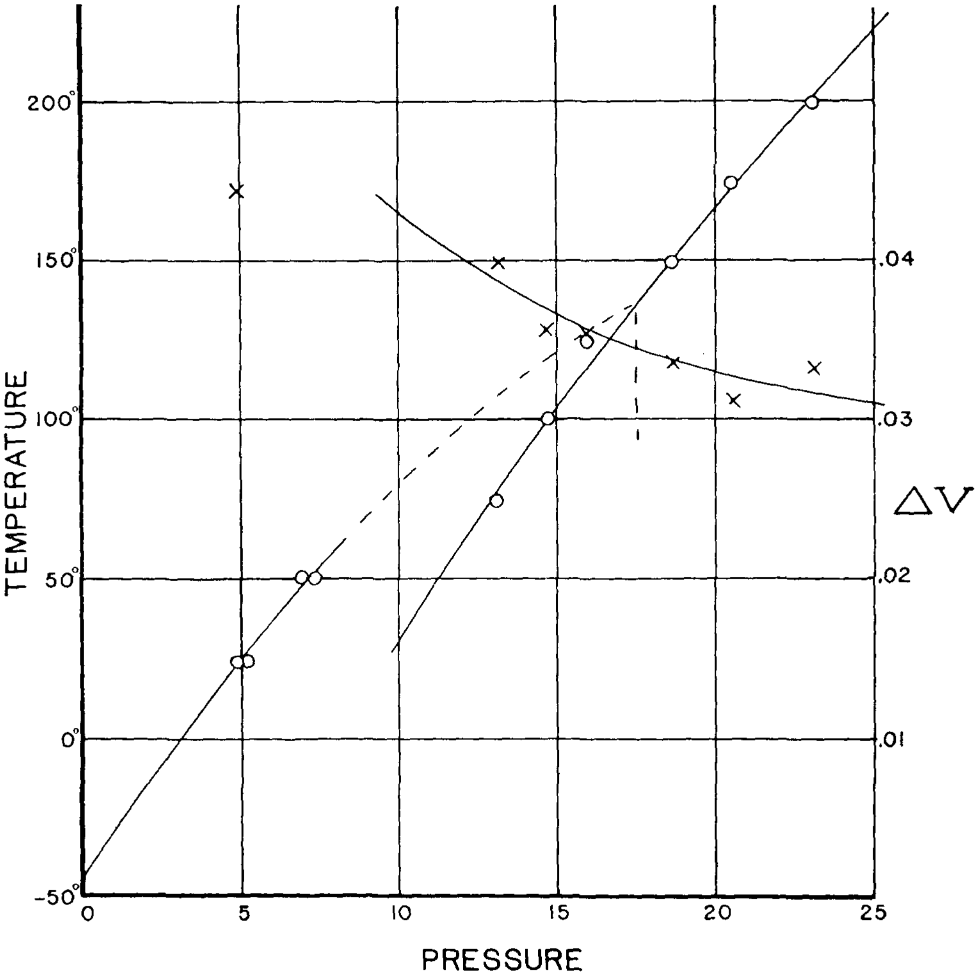

Fig. 8. The freezing parameters of chlorobenzene. The freezing temperatures are shown by the circles, with the scale to the left, and the *fractional* changes of volume by the crosses, with the scale to the right. The location of the triple point and the transition line between the two varieties of the solid is highly hypothetical.

The compressions are given in Table XXV. The normal freezing point is 10°, so that these measurements are all on the solid phase.

Cyclohexane. The source of the material was Timmermans.[11]

Compressions were measured at all four temperatures with two different set-ups at each temperature and in four different pressure vessels. This material freezes at low pressures and rough values of the freezing parameters were determined incidentally in the course of the compression measurements. These freezing parameters are rough both because the special procedure for obtaining freezing parameters was not followed, and because the pressures were too low. In view of this, no effort was made to follow the freezing curve to higher temperatures.

At 25° the two compressions at the maximum pressure differ from the mean by 1.4% and at 75° by 0.02%, at 125° by 2.1%, and at 175° by 0.8%. There are no previous values for comparison. The compressions at the lowest pressures are more irregular than usual, and the adjustments are to a certain extent arbitrary.

The compressions are given in Table XXVI. The sequence of the values for change of volume on freezing is doubtless not as good as it would have been if direct determinations had been made of the melting parameters.

Methyl Cyclohexane. The material was old stock from Timmermans.

Compressions were measured at 25° and 75°. At each temperature four runs were made with four set-ups and two pressure vessels. Freezing

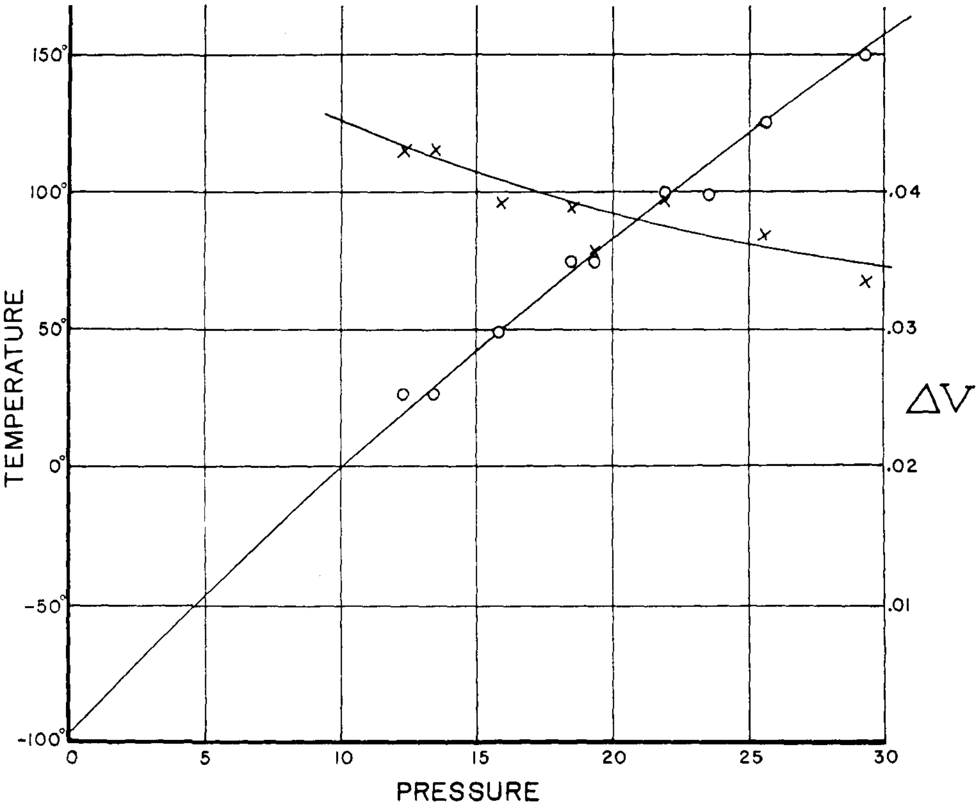

Fig. 9. The freezing parameters of methylene chloride. The freezing temperatures are shown by the circles, with the scale to the left, and the *fractional* changes of volume by the crosses, with the scale to the right.

occurs at comparatively low pressure, but freezing is very sluggish and if the normal time schedule is adhered to some of the subcooled liquid is carried up to the maximum pressure in spite of the fact that it is in contact with the solid. One half the runs were of this character. A rough estimate of the amount of liquid so carried in the unstable state to the maximum pressure can be obtained from the volume discontinuity at the melting point on release of pressure. To get the compressions of the pure solid phase, the regular time schedule had to be given up, delaying in the neighborhood of the freezing pressure until freezing was complete.

There are no previous values at the low pressures for comparison; on the other hand, at pressures below the melting point the compressions are now the average of four determinations instead of two as usual, and therefore should be more accurate. At 25° the deviation from the mean of the two runs on pure solid at the maximum pressure was 0.8% and at 75° 0.9%.

The compressions are given without attempt at correction in Table XXVII. It is not probable that the abnormal sequence of volume discontinuity on freezing between 25° and 75° is correct. From the measurements on the partially frozen liquid the following rough statements can be made; at 25° the compression between 20,000 and 50,000 of the subcooled liquid is 0.017 greater than that of the solid; at 75° the corresponding excess between 25,000 and 50,000 is 0.007. The first of these two values is to be given greater weight, being the average of two determinations differing from the mean by 10%, whereas the latter rests on only a single measurement under more unfavorable conditions because the quantity of liquid remaining unfrozen was only one half as great.

p-Xylene. The material was from Timmermans.

Compressions were measured at 25° and 75°, with two different set-ups at each temperature and in two different pressure vessels. Freezing occurs at pressures below 5,000, so that the measurements are for the solid phase. At 25° the

TABLE XXVI

CYCLOHEXANE

ΔV, cm^3 per 0.779 gm, from 5,000 kg/cm^2 as zero

Pressure kg/cm^2	ΔV			
	25°	75°	125°	175°
5,000	.000	.000	.000	.000
7,500	.028 .069 }*			
8,700		.043 .078 }*		
10,000	.084	.088	.055	.064
11,270			.066 .100 }*	
14,180				.098 .131 }
15,000	.110	.119	.125	.136
20,000	.130	.141	.150	.164
25,000	.146	.158	.169	.184
30,000	.160	.173	.183	.199
35,000	.171	.185	.195	.210
40,000	.181	.195	.205	.220
45,000	.190	.204	.212	.227
50,000	.198	.212		

* Solid at higher pressures.

two compressions differed from the mean at the maximum by 1.7%, and at 75° by 3.1%. There are no previous values of compression for comparison or correction.

The compressions are given in Table XXVIII.

Water. The material was distilled water from the laboratory tin still, freed from air by boiling in vacuum.

The freezing parameters have already been determined[20] up to 190°. The particular object of the present measurements was to get compressions of both liquid and solid phases over as wide a range as possible. The compressions were measured at the four temperatures, with two set-ups at each temperature and with four pressure vessels.

In order to secure agreement with the previously measured volume decrements between 5,000 and 10,000, an additive correction of − 0.0013 was applied at 25° and of − 0.0038 at 75°. At the two higher temperatures there are no previous direct measurements for comparison, but extrapolation gave an additive correction of − 0.0022 at 125° and − 0.0024 at 175°. In addition, corrections had to be applied to bring about reconciliation with the previous volume

TABLE XXVII

METHYL CYCLOHEXANE

ΔV, cm^3 per 0.764 gm, from 5,000 kg/cm^2 as zero

Pressure kg/cm^2	ΔV	
	25*	75°
5,000	.000	.000
10,000	.056	.062
13,800	.086 .113*	
15,000	.118	.099
18,800		.120 .149*
20,000	.137	.153
25,000	.152	.169
30,000	.166	.183
35,000	.177	.195
40,000	.187	.206
45,000	.195	.215
50,000	.203	.223

* Solid below this.

TABLE XXVIII

p-XYLENE

ΔV, cm^3 per 0.861 gm, from 5,000 kg/cm^2 as zero

Pressure kg/cm^2	ΔV	
	25°	75°
5,000	.000	.000
10,000	.029	.035
15,000	.051	.057
20,000	.069	.074
25,000	.083	.088
30,000	.095	.100
35,000	.105	.111
40,000	.113	.120
45,000	.121	.129
50,000	.128	.137

TABLE XXIX

WATER

ΔV, cm^3 per 1.000 gm, from 5,000 kg/cm^2 as zero

Pressure kg/cm^2	ΔV			
	25°	75°	125°	175°
5,000	.000 (.873)	.000 (.893)	.000	.000
9,800	.057 .127*			
10,000	.128	.063	.066	.070
15,000	.147	.105	.112	.120
20,000	.162	.136	.146	.157
21,430		.144 .236‡		
22,270	.169 .226†			
25,000	.234	.247	.173	.185
28,140			.186 .267‡	
30,000	.247	.260	.272	.207
35,000	.256	.270	.284	.226
36,560				.231 .302‡
40,000	.266	.278	.294	.310
45,000	.274	.286	.302	.317
50,000	.281	.293		

* Transition from liquid to Ice VI.
† Transition from Ice VI to Ice VII.
‡ Transition from liquid to Ice VII.

discontinuities at the phase changes. At 25° the maximum such adjustment was 0.004, at 75° 0.004, at 125° 0.006, and at 175° 0.003.

The compressions are shown in Table XXIX.

DISCUSSION.

The Melting Curves. The most important question to be answered by these new data is whether in the extended pressure range the melting phenomena begin to show any new tendencies not manifested by the previously determined curves, which were confined, except for water, to a pressure range of 12,000 kg/cm^2. Of the imaginable new tendencies, the termination of the melting curve in a critical point between liquid and solid would be certainly the most important. The possible existence of such a critical point has been brought up again recently by certain new theories of the liquid state and of melting.[3]

The thermodynamic earmarks of a critical point are the simultaneous vanishing of the difference of various thermodynamic properties of the two phases, such as the volume discontinuity, latent heat, entropy difference, and *difference of internal energy*. All of these, when plotted against pressure or temperature along the melting line, should vanish or tend to vanish simultaneously at the same pressure and temperature. The most casual inspection of the tables of melting parameters shows that this is even less the case than in the previous range. The reader will find it profitable, I think, to plot from the tables of melting parameters the slope, that is $d\tau/dp$, the volume discontinuity, the latent heat, the difference of energy, and the difference of entropy, all against temperature along the melting curve. Of these quantities Δv always decreases with increasing absolute temperature, and with but one exception, ethyl bromide, the curve of Δv is always convex toward the temperature axis in such a way as to afford no expectation that the curve will ever cross the axis at any finite temperature. The curve for ethyl bromide is linear, and a linear extrapolation would give a vanishing Δv at 140°, beyond the range of the measurements. I think, however, that one is entitled to disregard this example, when it is considered that the experimental error was unusually great, the whole curve resting on only three points, at the last of which a superpressure of 17,000 kg/cm^2 was required to produce freezing, and that this is the only example of such behavior of Δv among the substances of this paper or the many previously examined in a lower pressure range. The significance of this behavior of Δv, considered by itself and apart from the simultaneous behavior of the other parameters, is thus that there is no indication at present of the ultimate appearance of a critical point in the melting curve. No more is there any indication of a maximum, for a maximum means a vanishing of Δv at a finite temperature. Furthermore, if there were a maximum, the Δv curve would plunge vertically into the temperature axis, and the curvature is in the wrong direction for this.

The conclusions from an examination of the behavior of Δv alone are only reinforced when the simultaneous behavior of the latent heat, energy and entropy differences are considered. There is no tendency for any of these quantities to vanish at any finite temperature, to say nothing of any possible simultaneous vanishing with Δv. The curves for these three quantities in general rise, or if they fall, it is only by small amounts and irregularly. The superficial appearance of the graphs for these three quantities suggests a qualitative difference of behavior in this new high pressure range compared with the previous results to 12,000. Formerly, the latent heat had roughly a tendency to remain constant, or if it increased, the increase was in all cases less rapid than the increase in absolute temperature, so that in all cases the entropy difference between solid and liquid decreased with rising pressure and temperature along the melting curve. Now, in the new range, the general impression is that the latent heat tends to rise more rapidly with temperature, and in fact the rise is so rapid that now there are several cases of an increase of entropy difference along the melting curve. It may possibly be only fortuitous that these cases of increasing entropy difference appear to be associated with an increase in the pressure range, for it is to be considered that now several so-called abnormal substances have been taken within the scope of the measurements. There are only three substances which exhibit this increase of entropy difference to a marked degree, water (the parameters of which beyond 12,000 had been previously determined), ethyl alcohol, and n-butyl alcohol. The alcohols are known to be abnormal in certain respects, and water is certainly considered abnormal. Two other substances of this paper also show an increase of entropy difference, chlorobenzene and carbon bisulfide, but the increase is only slight. A rough characterization of the substances of this paper in the new high pressure range is that with the exception of water and the two alcohols the entropy difference between solid and liquid tends to remain constant with rising pressure and temperature along the melting curve. There are obviously two factors affecting the entropy difference: it tends to increase because of increasing temperature, and tends to decrease because of the decrease of volume with increasing pressure. With the exceptions noted, these two tendencies roughly compensate each other. It will appear later that in general the effect of pressure on *volume* along the melting line is dominant over that of temperature, so that in general the volume of both liquid and solid phases decreases with increasing pressure along the curve, in spite of the effect of temperature in the opposite direction.

There is a characteristic difference between the jump in internal energy for the transition from solid to liquid compared with the transition from one solid to another. It has been found in previous work that at pressures above 12,000 there is an increasing tendency for the term $p\Delta v$ to become numerically greater than the latent heat, so that for almost all polymorphic transitions between solids at high pressures the phase stable at the higher pressure, that is, the phase with smaller volume, has a greater internal energy than the low pressure phase, in spite of the fact that passage from low pressure to high pressure phase may be accompanied by an emission of heat. With melting, on the other hand, although the term $p\Delta v$ increases with increasing pressure over the entire range for all substances, numerically it shows no indication that it will ever become large enough to neutralize the latent heat, so that the internal energy of the solid remains less than that of the liquid over the entire range. Except for the two alcohols and water, the difference of internal energy is very nearly constant over the entire pressure range, and is roughly of the order of one half the latent heat. Incidentally the fact that $p\Delta v$ rises over the entire pressure range indicates by extrapolation that Δv will not vanish at any finite pressure.

In spite of the fact that the two alcohols and water belong to the so-called abnormal liquids, I think in speculations on theories of the liquid and of melting considerable significance should be attached to the rapid rise of latent heat and entropy difference for them. In particular, water at high pressures is supposed to have lost the abnormalities which disturb it at ordinary pressures, so that at high pressures its structure should be among the simplest of all liquids measured here, and its behavior accordingly more significant.

The behavior of $d\tau/dp$ is capable of giving some information about the general shape of the melting curve. When plotted against temperature, in all these cases, as also in all previous cases, curves are obtained which are convex toward the temperature axis in such a way as to give no justification for the expectation that they will cross the axis at any finite temperature. If there were a maximum, the curves would plunge vertically into the temperature axis, with concave curvature, and if there were a horizontal asymptote, the curves would cut the axis at a finite temperature.

The general conclusion from this new work in a pressure range three or four times the previous range (except for water) is therefore the same as the conclusion from the previous work, namely that the melting curves of all measured substances are alike in being inconsistent with the existence of either critical point, maximum temperature, or temperature asymptote, and furthermore, they all indicate positively that the curves continue to rise to indefinitely high pressures and temperatures, with continually decreasing slope $d\tau/dp$ and continually decreasing volume discontinuity between solid and liquid. This new work suggests that at increasingly higher pressures cases become more numerous in which the entropy difference between solid and liquid increases along the melting line; there is no experimental basis for the expectation that this entropy difference will ever vanish.

Compressions. Perhaps the most immediately striking thing about the compressions is the narrow numerical range of the total compressions between 5,000 and 50,000. For nearly all the substances of this paper these cluster in the range 0.20 to 0.25, whether or not freezing occurs in the range. Three substances, benzene, ethyl bromide and p-xylene, are lower, being in the range 0.15 to 0.20, but these substances are solid over the entire range of measurement. Curiously enough, in view of the fact that at low pressures water is much less compressible than the average organic liquid, water is the only substance with compressions greater than the norm, its compressions lying between 0.27 and 0.33. The unusually large total compressions of water are due to the unusually large volume changes which accompany the phase changes. Compressions of the magnitude mentioned means for all substances, including water, that at 50,000 the absolute volume is surprisingly close to six tenths of the initial volume at atmospheric pressure.

A comparison of the compressions under more nearly comparable conditions would be obtained by comparing figures only for the solid phases. At room temperature, practically all the substances of this paper which freeze at all are solid at 25,000. In Table XXX are given the increments of compression on passing from 25,000 to 50,000. The range of numerical values, considering the range of composition of these liquids, is surprisingly low, from 0.045 for p-xylene and 0.047 for water to 0.059 for carbon bisulfide. The substances which are liquid in the range above 25,000 have, with the single exception of methyl alcohol, compressions larger than those of the solids, but even for the liquids the extreme figure is only 0.070 for n-butyl bromide. If it is true that the major part of the compressions at these high pressures is afforded by the compression of the atoms themselves, then the atoms which enter into the composition of these substances must have approximately the same compressibility. It must be more or less fortuitous, however, that the particular elements of these substances have such similar compressibilities, because there are plenty of other elements with greatly differing compressibilities, as may be seen from a table of the compressions of 17 elements up to 100,000 kg/cm^2 just published.[21]

TABLE XXX

Volume decrements between 25,000 and 50,000 kg/cm^2

Solids		Liquids	
Methyl Alcohol	.053	Methyl Alcohol	.054
Ethyl Alcohol	.057	n-Propyl Alcohol	.067
n-Butyl Alcohol	.053	i-Propyl Alcohol	.066
Ethyl Bromide	.059	n-Amyl Alcohol	.063
n-Propyl Bromide	.045	n-Butyl Bromide	.070
Ethyl Acetate	.054	Ethyl Acetate	.061
n-Amyl Oxide	.059		
Chloroform	.054		
Carbon Bisulfide	.059		
Benzene	.055		
Chlorobenzene	.054		
Methylene Chloride	.051		
Ethylene Bromide	.055		
Cyclohexane	.052		
Methyl Cyclohexane	.051		
p-Xylene	.045		
Water	.047		

A corollary of the close similarity of the curves of compression against pressure of the various substances is the similarity of the curves of compressibility, or first differences of the tabulated compressions. The mean compressibility in the range 5,000 to 10,000 averages about 0.000012, and in the range 45,000 to 50,000, 0.0000018. Variation from these figures of more than 10% is not common. Roughly, the compressibility $(-(\partial v/\partial p)_\tau)$ varies inversely as the pressure, which means that volume as a function of pressure is approximated by the formula $v_0 - v = \text{const.} \log p/p_0$, taking p_0 in the neighborhood of 10,000. This is the same simple formula that I found a number of years ago[22] approximately to reproduce the behavior of liquids in the range between 1,000 and 12,000. The formula evidently is not good for indefinite extrapolation, because it demands negative volumes at sufficiently high pressures. However, the pressure at which volume would become negative is of the order of 10^7 kg/cm^2, far beyond the present experimental range.

The compressions of the liquid and the solid phases are not of different orders of magnitude; as an average the compression at the maximum pressure of the solids of this paper is 25% less than that of the liquids. There are no cases in which the compressibility increases at the reversible freezing point on passing from liquid to solid, and in most cases there is a distinct decrease. There are a few cases, however, of which methyl and ethyl alcohols are examples, in which any drop of compressibility at the freezing point is within experimental error. In even these cases however, there is an obvious drop in the second derivative of volume with respect to pressure, the compressibility of the solid dropping off with increasing pressure at a less rapid rate than that of the liquid. In those cases where measurements can be made on both solid and subcooled liquid over a wide pressure range, the compressibility of the liquid remains greater than that of the solid at the same pressure over the entire range, the volume of the liquid continually approaching that of the solid as pressure increases.

The compressions are considerably greater at the higher temperatures for all substances. In computing the results no cross smoothing with respect to temperature on the isobars was attempted, so that the spacing of the isotherms in the tables is not always regular, and may well be in error. On the whole the spacing of the isotherms is as smooth as one has a right to expect. A higher compression at higher temperatures means that thermal expansion decreases as pressure rises. The numerical value of the change in thermal expansion can be found only in those cases where there are absolute values of the volume at 5,000 from previous work. Where the absolute values are known it will be found that there are very considerable decreases in thermal expansion; thus for methyl alcohol the thermal expansion at 50,000 is only one third or one quarter of what it is at 5,000. Isolated cases will be found in which apparently a negative thermal expansion is demanded at the highest pressure; this I think is not to be taken seriously but is to be ascribed to experimental error.

The accuracy of the measurements is not sufficient to permit any statement about the behavior of the derivative $(\partial^2 v/\partial\tau^2)_p$ at high pressure. Neither is the accuracy high enough to give any certain information about small scale irregularities such as were found in previous work.[6] These abnormalities might consist in an increase of compressibility or of thermal expansion with increasing pressure. Such abnormalities were always local, confined to a comparatively narrow pressure range. These abnormalities appeared to be characteristic of the individual substances at high pressures, and were supposed to arise from the irregular shapes of the molecules. There is no reason to think that such abnormalities do not continue into the pressure range of the present work, and in fact a number of examples were found. The accuracy was not great enough, however, to give sufficiently reproducible values for any such irregularities and the best course seemed to be to smooth right across them. In view of the approximately equal compressions of the different kinds of atoms of which the substances of this paper are composed, one would perhaps expect that such abnormalities would tend to become less at these high pressures.

The answers to certain general questions with regard to the behavior of the individual pure phases along the melting line are suggested by the regularities presented by the compressions. The first question is: does the volume of the single phases, solid or liquid, increase or decrease along the melting line? There are obviously two opposing tendencies; because of the rising temperature the volume tends to increase and because of the rising pressure it tends to decrease. The analytic expression is:

$$\left.\frac{dv}{dp}\right|_{\text{melting}} = \left(\frac{\partial v}{\partial p}\right)_\tau + \left(\frac{\partial v}{\partial \tau}\right)_p \frac{d\tau}{dp}.$$

The first term on the right is negative and decreases numerically along the line; the second term is positive and each of its factors decreases. It appears that in general the negative term is greater than the positive term, and remains greater at high pressure, so that in general the expectation is that the volumes of the pure phases decrease along the melting line, the increasing pressure overbalancing the increasing temperature. The data of this paper permit evaluation of the exact numerical values in those cases where the volume at 5,000 has been determined. Thus for water the volumes of the liquid on the melting line at 75°, 125°, and 175° are 0.749, 0.728, and 0.700 respectively. The corresponding values for the solid are 0.657, 0.647, and 0.629. Or the volumes of liquid ethyl alcohol on the melting line at 25° and 75° are 0.691 and 0.662, and those of the solid 0.656 and 0.629.

Or we may ask whether the internal energy of the pure phases increases or decreases along the melting line. The analytical expression for this is:

$$\left.\frac{dE}{dp}\right|_{\text{melting}} = -\left[\tau\left(\frac{\partial v}{\partial \tau}\right)_p + p\left(\frac{\partial v}{\partial p}\right)_\tau\right] + \left[C_p - p\left(\frac{\partial v}{\partial \tau}\right)_p\right]\frac{d\tau}{dp}.$$

The two terms in the first bracket on the right hand side are of opposite signs; initially the first of the two preponderates, and the sign of the whole is negative. But at higher pressures the term $p\left(\frac{\partial v}{\partial p}\right)_\tau$ tends to remain constant whereas $\tau\left(\frac{\partial v}{\partial \tau}\right)_p$ decreases. Substitution of numerical values for methyl alcohol shows that at 50,000 the sign has reversed and become positive, having started at 10,000 as negative. The second cluster of terms on the right includes only one negative term. $\frac{d\tau}{dp}$ is positive and becoming less. C_p, judging from the known behavior in the low pressure range more accurately measured, at first decreases slightly with rising pressure, but then reverses and at higher pressures increases moderately. $p\left(\frac{\partial v}{\partial \tau}\right)_p$ increases numerically because of the factor p in spite of the decrease of $\left(\frac{\partial v}{\partial \tau}\right)_p$, but numerically it is much less than C_p, and without doubt remains less, so that the second cluster of terms is always positive. On the whole therefore $\frac{dE}{dp}$ remains positive as pressure increases indefinitely along the melting curve, and the energy of the pure phases therefore increases.

Finally, it is to be considered what substances are brought to freeze by the application of pressure. If we accept at its face value our generalization about the universal character of the melting curve, temperature rising indefinitely with rising pressure, it would mean that any substance can be brought to freeze at any temperature by the application of sufficiently high pressure. The numerical values are such that it is a fair expectation that 50,000 should be high enough to bring this about at room temperature for substances ordinarily liquid, except perhaps for some of the permanent gases. Of the gases perhaps only hydrogen and helium are candidates when it is considered that the melting temperature of nitrogen is elevated 86° by only 6,000 kg/cm^2 and that of argon 109° by the same pressure.[23] In spite of this expectation four of the 21 substances examined here have not been brought to freeze; these are: n- and i-propyl alcohol, n-amyl alcohol, and n-butyl bromide. The factor which negatives the expectation deduced from the universal behavior of the melting curve is evidently the enormous sluggishness of activity in the liquid at high pressures, which may have as a special result greatly increased subcooling before freezing will start, and after the nucleus of the solid has been formed, enormously retarded velocity of the reaction from liquid to solid. The case of methyl cyclohexane will be recalled in which liquid and solid phases were simultaneously present for more than one hour, during which barely one tenth of a total volume of less than 1 cm^3 crystallized. The enormously increased viscosity of many liquids produced by pressure is evidently another aspect of the same phenomenon.[24]

It would appear then that as a practical matter one may expect certain liquids will never be made to freeze by any pressure no matter how high. What a sufficient criterion might be of what these liquids are does not at present appear; it is curious that among the alcohols it is the alternate members of the series. Doubtless small amounts of impurity play an important part here. It is probable, furthermore, that liquids which cannot be made to freeze by any pressure will nevertheless be solids in the popular sense at high pressures, being in the glassy state, so that as far as certain classes of phenomena go, they might as well have frozen in the technical thermodynamic sense. The applications to geophysics need not be elaborated.

In spite of the enormously increased sluggishness of many of these substances with respect to freezing, melting always occurred, as closely as could be told, immediately on crossing the thermodynamic melting line, so that the generalization remains that solids cannot be superheated with respect to the liquid. The only exception known is the case of certain complex silicates reported from the Geophysical Laboratory a number of years ago.

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PRESSURE-VOLUME RELATIONS FOR SEVENTEEN ELEMENTS TO 100,000 kg/cm²

By P. W. Bridgman

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CONTENTS

Introduction and General Method

This paper describes the first results of measurements above 50,000 kg/cm^2 in which the high pressure vessel is itself completely immersed in a liquid subjected to a pressure which in these experiments ranged from 25,000 to 30,000 kg/cm^2. A brief preliminary notice of the method has already been given.[1] The advantage of supporting the high pressure vessel with a liquid under pressure is two-fold: the maximum pressure is extended by the pressure of the liquid, and the intrinsic strength of the materials of the high pressure vessel is increased by the supporting pressure beyond the normal value. This increase of strength, however, is not as great as at first appeared, as I have already discussed in another paper,[2] and furthermore, when accurate measurements are in question it is not possible to utilize all the potential increase of strength, because of the slow plastic flow which appears to be the accompaniment of such increase of strength as there is at the higher supporting pressures. The limit of these measurements, 100,000 kg/cm^2, was set by considerations of accuracy limited by plastic flow, and also by economy, the life of a vessel diminishing rapidly as the range is increased.

In broad outline the method is as follows. The material whose compression is to be determined is placed in a small high pressure piezometer, which consists of a small cylinder with pistons projecting from either end. This piezometer is placed inside the apparatus for 30,000 kg/cm^2 with which a number of measurements have already been made and which has been described in detail.[3] Pressure in the 30,000 apparatus is at first increased in the normal way by the advance of its piston. The various dimensions are so chosen that when the pressure in the 30,000 apparatus has reached approximately 25,000 its piston makes up on the pistons of the high pressure piezometer. Further advance of the piston of the 30,000 apparatus increases the pressure within the high pressure piezometer by much more than the increase in the liquid of the 30,000 apparatus because of the small volume within the high pressure piezometer. The proportions are so chosen that pressure within the high pressure piezometer reaches 100,000 kg/cm^2 when the pressure in the 30,000 apparatus has increased from 25,000 to something between 27,000 and 30,000, depending on the material. I gave up the device of maintaining pressure in the confining liquid constant by bismuth in transition, the present method being more convenient and sufficiently accurate.

The pressure within the high pressure piezometer is obtained from a measurement of the extra force on the high pressure piston given by an electrical device completely immersed in the surrounding liquid; this device will be described presently. The displacement of the high pressure piston is obtained from the measured displacement of the piston of the 30,000 apparatus. Error from distortion of various parts of the apparatus is eliminated by making the method differential, taking the difference of displacement for the material under investigation and some standard substance of such small compressibility that its value at high pressures may be safely assumed from an extrapolation of its values at lower pressures. The method is not accurate, therefore, for substances of too low compressibility. The result of the measurements, after various corrections have been applied, is the volume as a function of pressure from a zero set by the pressure in the confining liquid, about 25,000 kg/cm^2. Both normal volume compressions and volume changes due to polymorphic transitions are thus obtained; the latter are distinguishable from the former by their discontinuity. The measurements have to be supplemented by others below 25,000. The materials selected for measurement in the following include most of the metallic elements with sufficiently large volume changes to give acceptable accuracy.

DETAILS OF THE APPARATUS

The heart of the apparatus is of course the piezometer. At first I used vessels of heat treated alloy steels. It appears to be possible to reach 100,000 (75,000 differential) with these without rupture or too great permanent set, but the accuracy obtainable is low because of slow plastic flow and very large distortion, more than 10 per cent on the cross section, with resulting irregularities from hysteresis. A paper by Basset[4] gave me the idea that it might be possible to use containers of carboloy. I had previously rejected this idea, both because of the mechanical difficulty of drilling long accurate holes in carboloy, and because of my fear that carboloy containers would rupture under internal prssure, carboloy normally being notably less strong than steel in tension and breaking with a brittle fracture in striking contrast to its much greater strength in compression. However, it appeared that Basset had used carboloy cylinders with external shrunk-on steel sleeves to support high internal pressure. One obvious great advantage of carboloy compared with steel is the much smaller elastic distortion, the elastic constants of carboloy being about three times greater than those of steel. It furthermore appeared on inquiry that the technique exists for drilling accurate holes in carboloy. Holes 0.31 inch long, 0.0625 inch in diameter, accurate to 0.0001 inch, have been made for me both by the Carboloy Co. and by Mr. Fred White.

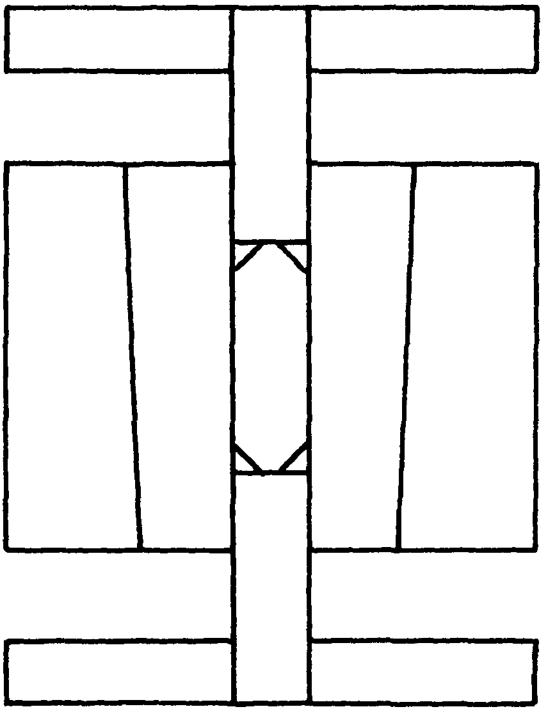

FIG. 1. The piezometer, consisting of a core of carboloy forced into a conical steel sleeve.

The piezometer is shown in Figure 1. The hole is first drilled in a suitable carboloy cylinder, which is then mounted on an arbor and the outside ground to a slight taper true with the hole. The tapered carboloy cylinder is then forced into a tapered external sleeve of heat-treated alloy steel in order to strengthen the carboloy to resist internal pressure by thus subjecting it to an initial compression. The taper used was about 0.004 inch in the length of the carboloy, and the amount of compression was sufficient to expand the steel by 0.002 inch. Under this compression the internal hole in the carboloy diminishes perceptibly, by something of the order of 0.0001 or 0.0002 inch. The amount of expansion which the steel will safely stand must be determined by trial. If the steel is too hard it may split off the carboloy core after standing for some time and after everything appears to be safely consummated. The brittleness of the carboloy in extension is shown by the fact that when the carboloy suddenly expands under the release of compression by the steel it may fly to pieces by its own inertia; I lost two carboloy cylinders in this way. With the dimensions shown the initial compression afforded by the steel sleeve probably did not rise above 15,000 kg/cm^2 and may well have been smaller. When immersed in the supporting liquid an additional compression results from the differential compressibility of steel and carboloy, but this effect amounts to the equivalent of only 2,000 or 3,000 kg/cm^2 at the maximum confining pressure. At the maximum internal pressure of 100,000 the carboloy is thus under a total compression of perhaps 45,000, 25,000 arising from the liquid and the balance from the steel ring, leaving 55,000 tension on the inside. Under normal conditions carboloy would break at a tension of less than half of this; that it is able to support it under these conditions must be an effect of the confining pressure.

Four piezometers have been used in this work, of different grades of carboloy. Two were of grade no. 905. The first of these broke after eleven exposures to about 100,000 and ten other exposures to from 80,000 to 90,000. The final rupture occurred with a filling of lithium, allowed to come directly in contact with the carboloy without protection, and at the time was ascribed to chemical action between lithium and carboloy, in analogy with the known chemical action under high pressure of sodium and steel. The conclusion was not checked, however, and in view of the life of the other piezometer of the same grade of carboloy, the natural life of the piezometer may have been reached and the connection with chemical action may have been only apparent. The second piezometer of no. 905 broke after seventeen applications of 100,000 or more; the final rupture occurred with a filling of indium, which is known not to exert any chemical effect on steel, at least in the range up to 50,000, and probably not to 100,000, because previously a successful run had been made with indium up to 100,000. A third piezometer of carboloy grade no. 779 ruptured on the second application of 100,000. The initial filling had been with arsenic, with no protection, and significance was ascribed to this, although again there was no check. The fourth piezometer of grade no. 55A has withstood sixteen applications of 100,000 or more, and is not ruptured at this writing. A considerably longer life was anticipated for grade no. 55A because at atmospheric pressure it is materially stronger in tension than no. 905.

These carboloy piezometers take a very small amount of set internally after exposure to pressure; the set can be detected delicately with the fingers in a greater looseness of the carboloy pistons, but is so small as to introduce no appreciable error, and does not appear to increase perceptibly as a prelude to rupture. The rupture may take the form of minute fissures permeating the mass of carboloy, but not penetrating through to the outside. After the rupture of the piezometer with indium little sheets and worms of indium continued to ooze slowly out of the inner wall of the piezometer for half a day.

The pistons of carboloy were forced into supporting discs of steel as shown; this both increases the strength of the pistons by supporting the ends and increases the accuracy of centering and alignment. The initial diameter of the piston was made about 0.0002 inch less than that of the hole. At the top pressure the pistons almost always received some shortening with corresponding increase of diameter. This plastic flow occurs over a wide range before rupture with slowly increasing velocity as the rupture point is approached. The result is that the force applicable to the pistons is much less when accurate measurements are demanded than the maximum possible on a quick application of pressure without rupture. Thus when pressure is rapidly applied up to the rupture point in compression I have measured[2] strengths ranging from 125,000 to 150,000 kg/cm^2, but under the slow increase of pressure required when measurements with the piezometer are made the shortening and consequent increase of cross section is already so great at 110,000 as to produce unpleasantly large friction of the piston in the piezometer. Carboloy differs from steel not only in its greater range of plastic flow, but also in its smaller work hardening; the pistons did not accommodate themselves to the maximum, but on every new set-up there was additional set after exposure to the maximum, and this did not tend to diminish markedly with repetition. After every excursion it might be necessary to reduce the diameter of the piston to its initial value by removing perhaps 0.0002 inch with fine diamond powder. The maximum permanent shortening in any of the following measurements was 0.004 inch on a total length of 0.3 inch; it usually fluctuated between 0.001 and 0.002. Most of the work was done with pistons of grade no. 905. Toward the end, however, grade no. 999, which has a smaller amount of cobalt, was tried, with much improved results from the point of view of permanent set. It does not appear, however, that the ultimate compressive strength of no. 999 is materially higher than that of no. 905; it is merely that it is more brittle and the plastic flow is slower. After a number of redressings the pistons become too much out of round and must be discarded. The life of the piston does not average more than half that of the piezometer.

The contents of the piezometer were prevented from leaking past the pistons by small conical packing rings as indicated. These are made of heat-treated alloy steel, drawn back far enough to be machinable in the lathe. The rings are made initially a drive fit for the piezometer. It was a gratification that there was not more difficulty from leak past the pistons, which I had feared. There was trouble from leak only once or twice and that with the softest materials. If the piston is made too small for the hole, the packing rings will crowd into the annular space between piston and piezometer wall, very much increasing the friction. As already mentioned, an initial clearance of about 0.0001 inch proved satisfactory. At the maximum pressure this clearance approximately doubles at the working end of the piston. The expansion of the bore of the piezometer is partly compensated by the expansion of the piston under compression.

There are two advantages in making the piezometer double ended with two pistons. Filling and emptying are much facilitated. Since the pistons move freely from each end, the effective length of the charge of the piezometer is halved. This reduces the frictional resistance to motion of the pistons arising from drag of the charge on the walls of the piezometer, which has the result of making the effective pressure at the center of the piezometer less than under the advancing end of the piston. Since the total frictional drag increases exponentially with increase of length of the piezometer, halving the length decreases the friction to less than one half.

The force with which the pistons are pushed into the piezometer by the advancing piston of the 30,000 apparatus is determined from the change of electrical resistance of a "compressometer." This has already been briefly described.[2] It consists of a cylindrical sleeve of heat-treated alloy steel cut longitudinally alternately from the two ends into a grid which offers a comparatively long path to the flow of current. The electrical resistance is measured on a potentiometer by methods previously extensively used and described in my work to 30,000. The electrical resistance changes by a certain fractional amount for a given intensity of compressive stress in the walls of the compressometer. Within limits set by feasibility of construction and mechanical stability the absolute resistance of the compressometer may be given any desired value for a given total compressive strength. Some little preliminary work was done in finding a suitable steel. Some grades of steel show hysteresis in the resistance as a function of compressive stress. The steel finally adopted was "Teton" steel of the Carpenter Steel Co., quenched into oil from 870° C. and drawn to 200° C. Compressometers of several different dimensions have been used for various purposes, depending on the total compressive force necessary to transmit. Two compressometers were used in this work, the first being ruptured by an explosion. The dimensions of these were approximately: length 0.29 inches, outside diameter 0.44 inches, wall thickness 0.032 inches, and resistance 0.045 ohms. The calibration of the compressometer will be described later.

The hydrostatic pressure in the supporting liquid was measured with a manganin resistance gauge, calibrated and manipulated as has been described in a recent paper.[5] The gauge demands one insulated lead and the compressometer three, thus demanding an insulating plug with four terminals. Gauge and compressometer were grounded to the cylinder of the 30,000 apparatus. In the early work with the 30,000 apparatus the insulated leads proved a major difficulty, not being able at first to stand more than two applications of pressure. In my last paper on measurements to 30,000 the use of a new design for insulating the stems was reported which appeared promising. This has been used in all this present work, with minor changes, and has fulfilled its early promise; it is not uncommon now to make 25 or 30 runs without renewal of the insulation. In fact, manipulation of the 30,000 apparatus has now become nearly as easy and as much a matter of routine as was formerly the manipulation of the 120,000 apparatus.

EXPERIMENTAL METHOD, CORRECTIONS, AND METHOD OF CALCULATION

The piezometer assembled inside the 30,000 apparatus ready for a run is shown in Figure 2. The piezometer is filled initially tightly with its charge by squeezing the pistons together in a vise. The amount of charge is determined from a measurement of the over-all length and the known length of the pistons. The amount of charge thus determined is corrected for the volume of the packing rings, which is obtained from their weight. The cross section of the piezometer is given accurately enough in terms of the diameter of the pistons. At first the section was determined by weighing the amount of mercury required to fill it, intending to follow up these measurements at intervals to check for permanent distortion. This more elaborate method proved unnecessary, however, but would have been necessary if the piezometer had been made of steel.

All of the contents of the 30,000 cylinder were inserted into it together in a single assembly. It will be seen from the diagram that the thrust is not transmitted directly to the pistons of the piezometer from the piston of the 30,000 apparatus, but there are several intermediate members. The use of all these intermediate members need not be described here in detail, some of them being atavistic survivals from former work. The principal of these members is a long rod of carboloy sliding concentrically within a steel tube within which the piezometer is

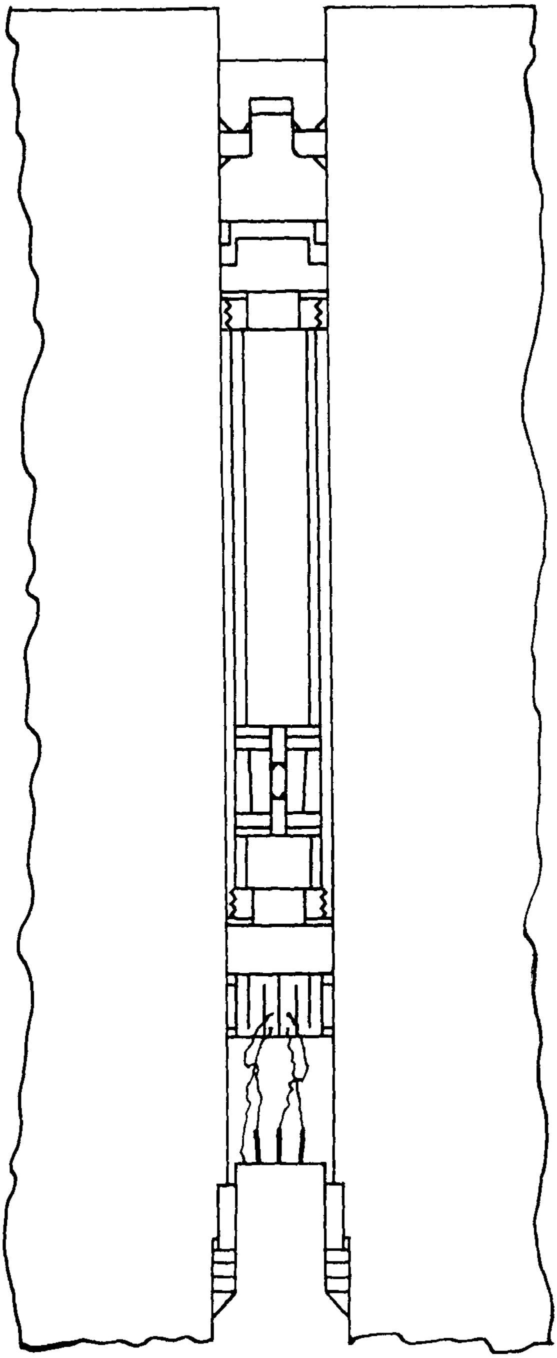

FIG. 2. General assembly; the piezometer within the cylinder in which the supporting pressure is generated.

also mounted. This carboloy compression member and the steel tube play an important part. While the confining pressure of 25,000 is being built up, the contents of the piezometer are of course being compressed, because they are completely bathed in the confining liquid. Because of the differential compressibility of the piezometer and its contents this means that when 25,000 is reached the charge of the piezometer no longer tightly fills it, but is separated from it by an annular film of liquid. When pressure is now increased in the piezometer beyond 25,000 a capricious amount of this annular film of liquid may be trapped between the charge and the walls, resulting in a spurious and too large an apparent compression. The effect is avoided by maintaining the pressure in the charge of the piezometer during the building up of the confining pressure always greater than the pressure in the confining liquid. How this is done is sufficiently indicated by the diagram. The piezometer is mounted inside a steel tube with screwed-in end plugs, and the balance of the interior of the tube is occupied with carboloy, which comes up tightly against the screw plugs. When confining pressure rises, the steel tube shortens more than the carboloy filler because of differential compression, with the result that the pistons are driven into the piezometer and the pressure on the charge kept greater than the pressure in the liquid, which therefore does not enter between charge and the walls. The result of this arrangement is that the first effect of applying thrust to the pistons of the piezometer by the piston of the 30,000 apparatus is to transfer strain from the walls of the steel tube to the compressometer, so that the displacements do not begin truly to correspond to compression of the contents of the piezometer until a pressure of 30,000 or 35,000 is reached. Before this arrangement was adopted many irregularities were found. If the charge is of unusually high compressibility, a tube of some more compressible substance than steel may be used, and in fact tubes of brass and of aluminum were used in the preliminary work. However, these did not prove to be necessary for the materials of this paper, although it may be desirable to return to them when measuring the more compressible salts.

The 30,000 apparatus, after assembly, is filled with iso-pentane as usual. The requisite amount of liquid so that the piston will make up on the piston of the piezometer at the requisite pressure has to be determined by trial. The amount of liquid was controlled by first filling the 30,000 apparatus and then expelling the superfluous liquid with a moderately tightly fitting plunger pushed in to a mark set by a screw stop. It was desirable to control the setting of this plunger to

0.010 inch. When working to such narrow tolerances the importance of freedom from leak is evident; this work would not have been possible unless practically complete freedom from leak had been attained.

After assembly, pressure is increased in the regular way by advancing the 30,000 piston. Pressure is measured on the manganin gauge. Simultaneously the resistance of the compressometer changes because of the increase of hydrostatic pressure to which it is exposed. This change of resistance is measured also, and a running plot made of the change of resistance of the compressometer against the change of resistance of the manganin gauge. In the range of pressures involved one resistance is a linear function of the other. When the 30,000 piston makes up on the piezometer, additional compressive stress is thrown on the compressometer, and its change of resistance deviates from the former direction because of the added effect of the one-sided compression. The running plot shows this deviation, and from now on manipulations are controlled by the running plot. Pressure is increased on the contents of the piezometer in steps of about 10,000 to the maximum and then decreased in similar steps.

The sensitivity of the galvanometer and other parts of the electrical set-up was such that settings could be made certainly to 0.1 mm. of bridge wire; readings of one resistance against the other were smooth to this amount. During the change of compressive stress on the compressometer its change of resistance arising from compressive stress was about twice as great as that arising from change of pressure in the confining liquid. The compressive stress was therefore determinable with an accuracy limited only by the sensitivity of the readings; at 100,000 this amounted to about one part in 150.

On release of pressure the pistons were measured for permanent set, and any such set applied as a constant correction to the displacement at the maximum pressure and all the subsequent displacements with decreasing pressure. Sometimes, if the reading next below the highest with increasing pressure was too near the highest reading, the effect of set could be detected there also, but as there was no way of knowing its exact amount, this reading had to be then disregarded.

Along with the electrical readings the position of the piston of the 30,000 apparatus was measured. After the piston makes up on the piezometer this gives, except for distortions in various parts of the apparatus, also the displacement of the piezometer piston, and thus eventually gives the compression. The displacement was measured with a jewelled Ames indicator, graduated to 0.0001 inch and allowing estimations to 0.00001 inch, attached to a point near the head of the carboloy piston of the 30,000 apparatus and the upper end of the 30,000 cylinder. The readings of this gauge were very smooth and satisfactory in every way. This gauge permits a fine control of the motion of the piston, which is very necessary when it is considered that the total motion of the piston of the piezometer from 25,000 to 100,000 may be as little as 0.020 inch. Positive control of the settings of the pistons proved to be feasible to a fraction of 0.001 inch.

All readings were made at room temperature, which averaged about 23°, without any attempt at control by a temperature bath, which would have been inconveniently cumbersome. If temperature drifts during a run, the zero resistance of the compressometer drifts also, and the extrapolated difference between the pure hydrostatic effect and the total effect is in error. Correction was made for drift by reading the temperature of the press at intervals during a run, which occupied on the average about two hours, by a thermometer inserted in a brass block soldered to a massive part of the apparatus. The total drift was always less than a degree Centigrade, and usually only a few tenths. The maximum correction for drift in any of the runs was equal to 0.8 mm. displacement of the slide wire setting, which means less than 5% on the differential reading of the compressometer which gives the force on the 100,000 piston.

The compressometer naturally has to be calibrated. At atmospheric pressure this offers no difficulty, and was simply accomplished in a small hydraulic press in which pressure was controlled with a dead weight gauge. The pure hydrostatic pressure coefficient obviously enters the results, but this can be determined in situ for every run from the readings before the piston makes up. The values so found were always consistent with each other. The difficulty is in finding the compression coefficient under hydrostatic pressure, for it would not be safe to assume that the compression coefficient is the same under 25,000 kg/cm^2 as it is at atmospheric pressure. Obviously a method of doing this "in principle" is to get the force on the compressometer from the excess force on the large piston of the 30,000 press when the compressometer is in action over that required to produce the same pressure in the liquid without the compressometer. The practical difficulties are the smallness of the excess force and the irregularities introduced by friction. The cross section of the 30,000 piston is 64 times that of the 100,000 piston, and the sensitiveness of the measurement of the high pressure in terms of the pressure driving the plunger of the large press correspondingly less than the sensitivity of measurement of the lower pressure, and it is known that this method is not satisfactory for the latter. However, it appeared that various refinements were possible, and I made some attempts to get a direct measurement by making a relatively insensitive compressometer so that during the calibration it could be stressed to a considerably higher compression than during the final measurements. These measurements were too irregular to be satisfactory, but did suffice to give a rough value for the effect. It appeared that frictional irregularity would probably always be too great to permit satisfactory individual readings, and the conclusion was finally reached to smother these irregularities by a great number of different set-ups. For this purpose it was fortunate that the pressure gauge with which the pressure driving the large piston of the 30,000 apparatus was measured was of an unusual degree of mechanical perfection. This gauge was of the Bourdon type, made 40 years ago by the Société Genevoise. It has a range of 1000 kg/cm², and has very seldom been used above 700. It was one which I had inherited from the late Professor T. W. Richards. It is graduated to 10 kg/cm², but the perfection of its multiplying mechanism is such that Professor Richards had attached at various fiducial points auxiliary scales graduated to 1 kg/cm², and was accustomed to make his readings with a glass to 0.1 kg/cm². I did not attempt any such refinements, but contented myself with readings to 1 kg/cm². The readings appear to be consistent at least to this limit, which is much better than I have been able to do with any gauge made in this country. The gauge has been calibrated from time to time against a dead weight gauge, and is satisfactorily constant.

Knowing the approximate value of the pressure coefficient of the compression coefficient, so that pressures could be kept within the desired range, the more exact value was found from a multiplicity of readings. Regular runs were made, and a record kept of all the changes of resistance and also of the pressure as recorded on the Geneva gauge. From these many readings, the normal reading of the Geneva gauge against pressure in the iso-pentane of the 30,000 apparatus was determined, and then the excess reading when the piston was made up on the 100,000 piezometer. The final results are from 16 complete runs, involving more than 300 points. Readings with increasing pressure and with decreasing pressure were treated separately to better eliminate friction. In getting the final grand average the results were weighted according to the absolute magnitude of the effect. The friction on the average was surprisingly small, being only 3.7%, which means that a reading with increasing pressure differs by 7.5% from a reading with decreasing pressure. This frictional effect is only that contributed by the two larger pistons; it does not include the friction on the small piston of the 100,000 apparatus, which naturally was much larger and also more irregular. Within the limits of error the change of resistance is linear in the compressive stress at any single confining pressure. The pressure coefficient due to the confining pressure is such that at 25,000 the compression coefficient is 15% less than at atmospheric pressure. There was no indication that this 15% is not linear in the confining pressure, and it was so assumed. If no correction had been applied for this effect, pressures would have been obtained at 100,000 15% too low. Since the confining pressure changes with increase of pressure in the 100,000 piezometer, the correction changes also, with the result that the compressive force on the compressometer is not a linear function of the deviation of the measured change of resistance extrapolated from the hydrostatic pressure part of the curve. Correction was made in the following for this deviation; the maximum error from this effect is about 4%. If the correction is not applied the pressures toward the maximum get too low, with the result that the compressibility at the high pressures would not drop off enough. The second compressometer, used after the first was fractured, was directly calibrated only at atmospheric pressure, assuming the same pressure coefficient of the compression coefficient. This seemed justified because the two compressometers were made from contiguous lengths of the same bar of steel, and their heat treatments were the same.

After the run was completed and the apparatus disassembled, the over-all length of the piezometer with pistons was again measured and also the dimensions of the pistons. Correction was applied for any permanent change of length as already described. The over-all length then afforded a check on permanent change of internal diameter of the piezometer; this practically never was found. The next step in working up the results was to convert the compressometer excess resistances, obtained by simple linear graphical extrapolation from a plot five times the scale of the slide wire readings, into actual pressures on the contents of the piezometer. This involves the cross section, and this demands a correction for change of cross section. This correction was calculated by conventional methods of the theory of elasticity, and need not be described in detail. Three different effects had to be taken into account: the effect of the confining pressure, the effect of the differential compressibility of the steel jacket shrunk on the carboloy core, and the effect of the internal pressure in the carboloy. The elastic constants of carboloy are approximately three times those of steel. The fundamental numerical value was taken as the value of Young's modulus which had been measured by Dr. Dennison Bancroft by a dynamic method on a number of different samples of grade no. 905 carboloy and found to average 64.5×10^{11}, Abs. C. G. S. units, with deviations seldom as much as one per cent. The other constants of carboloy were assumed to bear the same ratio to its Young's modulus as the other constants of steel bear to Young's modulus of steel. This assumption had been approximately checked by a direct measurement by me of Poisson's ratio for the same grade of carboloy. There is some evidence that the assumption may not be as good for other grades of carboloy, but the difference is probably unimportant. The correction calculated in this way is an increase of cross section of 3.2% at an internal pressure of 100,000 kg/cm^2 and a confining pressure of 25,000. This correction changes by 0.1% for a change of 5,000 in the confining pressure, an effect so small that it was neglected. At the working end of the pistons the correction is only one half as great. It was this correction that was applied in reducing compressometer readings to pressures. The full correction of 3.2% has to be applied at a later stage in reducing the observations.

In evaluating the corrections for distortion, two effects were considered which were neglected in my previous work to 50,000. In the first place, the ratio of diameter of piezometer to its length is only 3, so that it is to be considered whether end effects do not enter into the change of cross section, which was calculated from the simple formulas for infinitely long cylinders. In my previous work I had tried to convince myself by a crude graphical analysis that such effects were probably not important. Very recently, however, Dean Westergaard[6] has made a mathematical analysis of the problem which permits a much more satisfactory conclusion. It appears that the effect is not large enough to introduce appreciable error. Another consideration is that the strains are getting so large at these high stresses that it is conceivable that the ordinary theory of infinitesimal strains is not good enough, but should be replaced by the theory of finite strains which has recently been put on a satisfactory basis by Murnaghan.[7] It appears that in the case of steel this effect would have to be considered. Professor Murnaghan was kind enough to make the calculations, and found that for a cylinder with infinitely thick walls stressed by internal pressure to such a value that the classical theory of infinitesimal strains would indicate an increase of cross section of 10%, the more accurate theory of finite strains would give a result 8% smaller. This effect is proportional to the magnitude of the strain. The correction calculated above for carboloy would therefore be in error because of this effect by less than 3% of itself. Since 3% of a 3.2% correction is only 0.1% the effect need not be considered in this work.

The true pressures having been obtained, the next step was to plot the piston displacements against pressure, taking as the zero the displacement at which the piston first makes up. Smooth curves were then drawn through these points, one curve for increasing pressure and one for decreasing. The lowest point was likely to be off, because of the effect of the steel tube, as already explained, and was often discarded. Also the highest points on the decreasing curve had to be neglected, because for them the motion was not yet great enough to completely reverse the frictional effects. The mean curve was then drawn through the two curves, taking the mean pressures at constant displacement. It has already been explained in one of my papers dealing with measurements to 50,000 that this gives a better correction for the effect of friction than the mean displacement at constant pressure. From this mean curve the displacements at even pressure intervals were tabulated; the initial pressure was 25,000 (the average initial confining pressure in all the experiments), the next 30,000, and then 40,000 and at 10,000 intervals to 100,000.

From these tabulated displacements were then subtracted the displacements which had been obtained by an exactly similar procedure for the comparison runs with gold, which was chosen as the standard substance because of its low compressibility and mechanical softness, as already described. Four piezometers were used in this work and six calibrating runs were made with gold, two with each of the two piezometers most extensively used. All six calibrating runs agreed within 5% of themselves; part of the difference is to be ascribed to slight differences in the dimensions. The consistency of these calibrations was gratifying and better than I had expected. It does not appear that there is any significant difference in the different grades of carboloy, and the corrections calculated for grade no. 905 were applied throughout. There have been measurements of the constants of the various grades which support this procedure. The total displacement from 25,000 to 100,000 for the calibrating runs with gold was 0.020 inch. Of this total 0.006 is contributed by the compression of the gold, 0.005 by the change of cross section of the piezometer, and the balance by the distortion of the various parts of the apparatus.

The differential displacements give the differential compression of the material under examination and gold, except for various corrections. In the first place, this statement assumes that the distortions of the rest of the apparatus are the same for the run with gold and the other material. This is not quite true, the distortions of the apparatus depend both on the hydrostatic pressure prevailing in the fluid of the 30,000 apparatus, and the compressive force with which the pistons make up. The confining pressure in the run with gold rises at a slower rate than in the run with the material in question because of the smaller compressibility of gold, and a correction has to be applied for the lack of equality of the confining pressure in the two runs. This correction was determined by various dummy runs with the piezometer or other parts of the apparatus replaced by carboloy, and need not be described in further detail. The correction so determined averaged about 6% of the differential displacement.

Further reduction of the results to obtain finally the fractional change of volume in terms of the volume at atmospheric pressure as unity was sufficiently straightforward. A correction is involved approximately additively for the assumed compression of gold as a function of pressure, an approximately multiplicative correction for the full cross sectional distortion amounting at the maximum to 3.2%, and an approximately additive correction proportional to the product of the fractional distortion of the cross section and the difference between the initial volumes of the material in question and the gold of the calibrating run. This latter term is obviously small. The compressions assumed for the gold at the high pressures were computed by Murnaghan's formula with one constant combined with my experimental determination up to 12,000 using the corrected second degree term obtained from my measurements up to 30,000. The values thus assumed for gold were: 0.0133, 0.0255, and 0.0483 at 25,000, 50,000, and 100,000 kg/cm^2 respectively.

Most important of all the data necessary for the final reduction is the compression at 25,000 of the substance, since obviously all these measurements are from a zero of 25,000. This value was usually obtainable from preceding work.

Two runs with two fillings of the apparatus, often with different piezometers, were made for every substance but one. The final results are the average of the two runs, each computed as just described. This average was finally subjected to a smoothing for first differences; the final smoothing usually did not affect the last significant figures by more than one.

DETAILED RESULTS

There follows now the detailed presentation of results. These are all collected into a single table, which has already been presented in the Physical Review.[8] The arrangement is by columns in the periodic table.

The four alkali metals were measured by a different and less accurate procedure than all the others. The lower accuracy of the results for these metals is unfortunate, because it is just these which are simplest from a theoretical point of view and therefore most amenable to theoretical treatment. The necessity for a different procedure arose from the presumptive chemical action between the alkali metals and the walls of the piezometer. Such action was perhaps not conclusively established. It had been definitely established in my former work to 50,000 that there is such action with steel. On the first attempt in the present series of experiments to use

TABLE I

COMPRESSION OF SEVENTEEN ELEMENTS

Pressure Kg/cm²	Li	Na	K	Rb	Ca	Sr	Ba	Zn	Cd	In	Tl	Sn	As	Sb	Bi	Se	Te
10,000	0.074	0.117	0.183	0.233	0.058	0.075	0.086	0.016	0.022	0.023	0.023	0.018	0.047	0.025	0.028	0.089	0.045
20,000	.125	.182	.268	.316	.103	.122	.159(d)	.031	.042	.045	.043	.034	.083	.047	.052	.149	.079
30,000	.164	.232	.329	.371	.139	.172(b)	.211	.046	.060	.064	.061	.049	.109	.066	.158(h)	.187	.111
40,000	.201	.273	.377	.419	.168	.209	.253	.061	.076	.081	.079(f)	.064	.132	.083	.174	.208	.138
50,000	.237	.310	.419	.462	.195	.239	.288	.075	.091	.097	.103	.077	.152	.098	.192(i)	.227	.214(l)
60,000	.272	.343	.457	.501	.220	.266	.318(e)	.088	.104	.112	.119	.091	.171	.112	.205	.243	.225
70,000	.305	.372	.492	.539	.252(a)	.298(c)	.361	.100	.116	.126	.132	.103	.188	.124	.222(j)	.258	.234(m)
80,000	.336	.397	.522	.575	.268	.317	.382	.111	.127	.140	.145	.114	.204	.136	.232	.271	.250
90,000	.366	.419	.549	.608	.284	.335	.402	.122	.138	.153	.157	.125	.219	.185(g)	.240(k)	.283	.258
100,000	.394	.440	.573	.638	.298	.352	.420	.132	.148	.165	.169	.136	.233	.197	.261	.295	.267

(a) Transition at 64,000. Compressions: 0.229 and 0.242.
(b) Transition at 25,000. Compressions: .143 and .152.
(c) Transition at 65,000. Compressions: .279 and .287.
(d) Transition at 17,000. Compressions: .135 and .141.
(e) Transition at 60,000. Compressions: .318 and .337.
(f) Transition at 40,000. Compressions: .079 and .086.
(g) Transition at 85,000. Compressions: 0.142 and 0.179.
(h) Two transitions at 25.000. Extreme Compressions: .064 and .150.
(i) Transition at 45,000. Compressions: .180 and .186.
(j) Transition at 65,000. Compressions: .211 and .216.
(k) Transition at 90,000. Compressions: .240 and .252.
(l) Transition at 45,000. Compressions: .152 and .207.
(m) Transition at 70,000. Compressions: .234 and .241.

the regular method with lithium the piezometer ruptured before reaching the maximum pressure. The probability of chemical action seemed too great to risk the rupture of other piezometers. These alkali metals were therefore protected from direct contact with the walls of the carboloy piezometer in the subsequent work by being enclosed in a capsule of copper. Because of the great distortion, the capsule has to be made with heavy walls. The total volume of copper was twice that of the enclosed alkali metal. Even with this amount of copper the walls were thinned down to practically nothing in some places after a single excursion to the maximum pressure, so that it would not have been possible to use a smaller amount of copper in spite of its desirability from the point of view of accuracy. The capsule was sealed by spinning over the open end in the lathe, or in some cases by inserting a plug in the open end and giving a precompression in the piezometer. The amounts of copper and alkali metal were determined at first by weighing. The weight of the copper was of the order of 0.050 gm, and that of the alkali metal varied from 0.002 to 0.004 gm. This latter is so small as not to give the total amount with the desired accuracy, so that for the final calculations the amount of alkali metal was taken from the volume as given by the over-all length of the piezometer with pistons, assuming that the part of the volume occupied by the copper was given with sufficient accuracy by its weight because of its greater mass. The dimensions of the charge could be determined from the over-all length to about one part in 200. The volume of the alkali found in this way agreed within 10% with the less accurate volume given by the weighing.

The result of the measurements with the capsules is a compression contributed jointly by copper and alkali. To isolate the contribution of the alkali it is necessary to know the compression of copper. This is much smaller than that of the alkali, and I assumed that it would be given with sufficient accuracy by an extrapolation made by an application of Murnaghan's one constant formula to my values up to 12000, properly corrected, as in the case of gold. The values thus assumed for the compression of copper were: 0.0170, 0.0325, and 0.0608 at 25,000, 50,000, and 100,000 respectively. The contribution of the copper to the total compression varied from 15 to 20%.

This contribution by the copper is so small, because of the very high compressibility of the alkalies, that the accuracy would not be seriously limited by this factor. The limitation of accuracy arises from the great friction exerted by the copper, which is much harder than most of the other materials measured here. The uncertainty from this effect is particularly serious at the lower end of the curves. The result was that the agreement with my previous results in the common range between 25,000 and 50,000 was poorer than for the other materials. I believe the previous results are preferable, because the previous method should give its best results just for these metals because of their high compressibility. In view of this, the present results were corrected in the following way. The displacement at 50,000 was calculated which would have been necessary to make the present results agree with the former ones. The difference between this displacement and the actually observed one was then applied as an additive correction to all the observed displacements up to 100,000. The regular calculations applied to these displacements then gave a curve of compression which was continuous with the former curve of compression at 50,000, but which has a break in direction at 50,000. The final result was obtained by smoothing graphically this break in direction across 50,000. The results tabulated in the following are therefore controlled in the main by the former results below 50,000, but diverge somewhat from them, particularly toward the upper end of the former range, near 50,000. In addition to this special dependence of the results for the alkali metals on the previous measurements, the compressions at 25,000 and below tabulated in the following are lifted straight from previous work, as for all the other substances.

The magnitude of these adjustments is indicated by the following figures. For lithium the compression at 50,000 given by these measurements before application of any corrections was 0.263, as compared with the figure 0.233 from previous work; for sodium the corresponding figures are 0.371 and 0.306; for potassium 0.462 and 0.416; and for rubidium 0.520 and 0.449. The new work differs consistently from the old in giving higher compressions over the entire range. There is nothing inherently improbable, however, in the new values. Evidence as to internal consistency is given by a graphical examination. The decrease of rate of compression with rise of pressure must be such that the volume approaches zero asymptotically at infinite pressure. The graphs make such an asymptote appear reasonable. This requirement says more than might appear to on the surface, because with this particular arrangement, in which part of the compression is contributed by the copper, it is quite conceivable that values might have been obtained for the over-all compression which would appear reasonable from the point of view of the simpler procedure for the other substances, but which on calculation should yield a negative volume for the contribution of the alkali part at the highest pressures.

The only particular in which the results have a certain degree of antecedent improbability from the graphical point of view is for sodium; the compression of this seems to flatten out too rapidly at the highest pressures to be in line with the other alkalies.

A slight degree of presumptive evidence as to the accuracy of these results is given by the original single run on lithium before the capsule was used with increasing pressure up to nearly the maximum, where rupture occurred. In this run the material completely filled the piezometer, and pressure was transmitted directly to the carboloy by it. The compression at 100,000 given by this single run, which is too low because of friction, which could not be determined because there were no readings with decreasing pressure, was 0.348 against 0.394 listed above from the measurements with the copper capsule. No adjustments were applied to the figure 0.348 in the direction of agreement with former results.

There is no intrinsic reason why the measurements should not be made on caesium as well as on the four given. The apparatus was set up with caesium and measurements made up to the maximum, when a major rupture occurred, one of the supporting rings of the 30,000 apparatus which had been in use continually for several years, and the repair has not yet been effected. This single run permits only the statement that the compression of caesium remains greater than that of rubidium by something of the order of 15%.

The alkali metals were of adequate purity and were from my stock. They are the same as used in my previously reported measurements to 50,000.

One of the questions suggested by these measurements is whether the other alkali metals show polymorphic changes in the new range analogous to the transition of caesium at 23,000.[9] None were found. The volume change of the transition of caesium is 0.006. This is small, but several fold larger than is easily detectible by this method under normal conditions. However, it is not entirely ruled out that a transition of this magnitude might have been so smeared out by the friction of the copper as to escape detection.

As usual, the figures of the table are the average of two independent runs. Some additional indication as to the accuracy is given by the agreement of the two runs. For lithium, the compressions at 100,000 of the two runs differed by 1.9% of themselves, or 0.95% from the mean; for sodium the difference from the mean was 1.2%, for potassium the difference from the mean was 1.9% and for rubidium 6.2%. It is curious that the disagreement increases as the absolute compressibility increases.

The three alkali earth metals, calcium, strontium, and barium, were from the same supply as that used in previous measurements. The piston displacements were larger than for any of the other substances; the displacement for barium at 100,000 was 0.063 inch, more than three times the displacement for gold. These metals are soft and the width of the loop due to friction therefore small; for barium at the top pressure the friction loop was 10,000 kg/cm^2 wide, which means that rising and falling curves differ 5,000 kg/cm^2 from the mean, or 5%. Both the softness and the high compressibility of these three substances make for accuracy. For calcium the compressions of the two runs at 100,000 differed 0.9% from the mean. The average compression at 50,000 was 0.190, against 0.204 found previously. The former value was given some weight in selecting the value of the table at 50,000, which is given as 0.195. Calcium was found in the former work to have a transition in the vicinity of 25,000 or 30,000, but the volume change is small and the transition does not run cleanly enough to give good values for the parameters, so that the compressions of the former paper were smoothed right across the transition. Unmistakable evidence of a transition in the same locality was found in this present work also, but since its characteristics were no better than before, the parameters could not be evaluated, and the compressions of the table are smoothed across the transition as before. In addition to the transition already known, a new transition was found at approximately 65,000. This is much more clean cut and definite than the transition at lower pressures. The volume change for the new transition given by the two set-ups was 0.014 and 0.017.

The compressions at 100,000 of the two runs with strontium differed by 0.04% from the mean. At 50,000 the average compressions of these two runs differed by 0.6% from the former value. Strontium has a transition at 25,000, below the range of the present work, whose parameters were previously determined, and a new, small, but well marked transition at 65,000. The transition pressures given in the following for various materials make no great pretense to accuracy; the fact that pressures were usually altered in steps of 10,000 is not favorable to accuracy. The volume change for the transition given by the two set-ups was identical, 0.007.

The two set-ups with barium gave compressions at 100,000 differing by 3.7% from the mean. The second of these was weighted double in the final result because of greater completeness and regularity of the readings. At 50,000 the compression of these new measurements differs by 0.3% from that previously found. Barium has a well marked transition at 60,000 in addition to the one previously known near 15,000. The two set-ups gave identical values for the volume change of this transition, 0.019.

The next two metals of the table, zinc and cadmium, have compressions so small that the method is becoming less well adapted. The chief interest in measuring them was the possibility of transitions, which might perhaps be anticipated because they are both so strongly anisotropic in their properties under normal conditions. Cadmium is known to have a very small transition at low pressures.[10] The material in both cases was spectroscopically pure; the same stock has been used in previous work, and I owe it to the courtesy of the New Jersey Zinc Co. No new transitions were found. It is to be remembered that the compressions given in the following are average compressions for all directions in the crystal; the linear compressibility in different directions in the crystal varies by a factor of eight. The compressions at 100,000 of the two runs with zinc differed by 1.2% from the mean. There are no previous measurements to 25,000 for the fiducial initial compression. For this I assumed the value 0.038, obtained by an extrapolation of my second degree formula reproducing my results up to 12,000. In this, my recently redetermined value for iron was used, as in all similar cases in this paper. The compressions at 100,000 of the two runs for cadmium differed from the mean by 1.3%. There are no measurements of the compression of cadmium above 2,000. The reason for this is that previous measurements had been of the linear compressibility for different directions in the single crystal, and at 2,000 there is a small transition which changes the single crystal into a crystalline aggregate, and the method becomes inapplicable. The best that I could d for the fiducial compression of cadmium at 25,00 was to assume that the compressibility of cadmium retains over the pressure range up to 25,00 its initial ratio to that of zinc. This assumptio is perhaps not too unplausible in view of the ver small volume change of the transition, and th fact that there are many cases where polymorphic change occurs with small change in compressibility. The fiducial compressibility at 25,000 obtained in this way was 0.051. Its ratio to that of zinc is 1.35. At 100,000 the ratio of the compression of cadmium to that of zinc is 1.12. It would appear that probably the assumption of a constant ratio of the compressions of cadmium to zinc is at best rough even for the range up to 25,000.

Indium, the next metal of the table, was tried because of its softness, because it is compressible enough to come within the range of the method, and because its unusual crystal system, tetragonal, suggests the possibility of a transition. No transition was found. The material was the same as that used in my previous work to 50,000. Only one complete run was made with this material. The piezometer fractured at the maximum pressure on the second set-up, as has already been described. There was no perceptible difference between the parts of the runs with increasing pressure on the two set-ups, and there is no reason to expect that the accuracy of the final result differs materially from that of other substances. At 50,000 the compression of this new work differs by 3% from my former value. The former measurements were made with an early form of apparatus and were described as "rough." The new result is doubtless to be preferred.

Thallium, the next metal, is one of the more compressible metals and is known to have a well marked transition near 40,000. The same material was used as before, some highly purified material which I had inherited from the late Professor T. W. Richards. No new transition was found. For some unknown reason one of the two set-ups gave values below the transition at 40,000 which were impossibly high, as could be seen by extrapolating them graphically back to zero. Hence only the other run was used in making up the values below 40,000. Above 40,000 the differential compressions of the two runs were averaged. At 100,000 the two compressions given in this way differed by 3.6% from the mean. Again a well marked transition was found near 40,000. No very good values were obtained for the volume change, which was also the case in the previous work. One run gave 0.011 and the other 0.007, against the previous value 0.005. The value given in the table is 0.007, taking the one of the two values which is closest to the previous one. Evidently there is considerable uncertainty here. There are no previous measurements of the compressibility of thallium above the uncertain ones of Richards up to only 500 kg/cm^2. The reason that I have not attempted it myself to high pressures is that thallium is non-cubic and I have been waiting for a chance to make the single crystals. For the fiducial compression at 25,000 I assumed out of whole cloth that it is the mean of lead, 0.050, and indium, 0.054, this giving 0.052. The compressions below 25,000 listed in the table were obtained from this and the values at higher pressures by graphical extrapolation.

Tin, the next metal, is, except for zinc, the least compressible of the materials measured here. It is non-cubic, and therefore is a candidate for transition. None was found, however. The material was Kahlbaum "K" material obtained a number of years ago, which had been further purified by being made up into single crystals. The compressions at 100,000 of the two set-ups differ by 2.1% from the mean. At 50,000 the average compression of the two runs differed by 6.5% from the former value. However, the former value was one of my first measurements, recognized as "rough," and was probably among the least accurate of them. The new values indicate a smaller compressibility than the former rough ones. I think there is no doubt but that the new ones are to be preferred, and in the table the values at the low pressure end are adjusted to make smooth connection with the new values, rather than using the old values as usual.

Arsenic, the next element, is highly non-isotropic, and transitions might be expected both because of its occurrence in the same column of the periodic table with bismuth, and because of the known abnormalities at low pressures.[11] None were found, however. The material was originally from Kahlbaum, but it had been further purified by several distillations and by formation into single crystals. Purification of the original material is particularly necessary for arsenic, because it contains in the dissolved condition a large amount of its own oxide. The possibility of producing single crystals affords a sensitive test of its final purity. Only a single run was made with this material, the piezometer fracturing on the next filling, with gold. I feared the result of chemical attack and so did not risk other runs. There is therefore no internal evidence from which the accuracy of the final result may be estimated. It is probable, however, that it is less than usual. In spite of its high compressibility, arsenic is perhaps the hardest of the materials measured here, and the frictional hysteresis was unusually great. The only previous measurements of the compressibility are by Richards in the range up to 500 kg/cm^2. Over this range it is 2.6 times more compressible than zinc. I assumed that this ratio is maintained up to 25,000, giving a fiducial compression at 25,000 of 0.097. The listings in the table at lower pressures were obtained by graphical extrapolation.

Antimony has long been a candidate for a transition because its crystal structure is identical with that of bismuth. It is therefore gratifying that a transition was found, although at an unexpectedly high pressure, 85,000, against 25,000 for bismuth. The volume change is so large, nearly 4%, as to suggest that this is actually the same structural transition as the first transition of bismuth. The volume change was so large that settings could be made on the actual equilibrium with both phases present, the only one of the materials of this paper for which this was possible. The material was originally "K" material from Kahlbaum, made up into single crystals. At 100,000 the two compressions differed by 1.5% from the mean. At 50,000 the mean of the two present compressions differed by 1% from the former value. For the volume change at the transition the two runs gave 0.035 and 0.039.

Bismuth was an obvious candidate for examination because of its many abnormalities at atmospheric pressure and because it is known to have three transitions below 50,000.[12] Two new transitions were found, which means six modifications in all, making bismuth the most versatile known metal. There is a rather close parallel between the transition patterns for bismuth and for water; it will be recalled that both bismuth and water freeze with increase of volume, and that the melting curve initially drops with increasing pressure. The new transitions of bismuth take place at 65,000 and 90,000; the latter has the larger change of volume. The previous nomenclature will be extended, and the modification stable between 65,000 and 90,000 called bismuth V, and the one stable above 90,000 bismuth VI. The transition from IV to V is suppressed with increasing pressure, IV passing directly to VI. But with decreasing pressure the transition is resolved. A similar situation occurs under proper conditions with water.

The material was from my single crystal stock, which had been purified by a double electrolytic deposition. At 100,000 the compressions of the two set-ups differed by 4% from the mean, a greater discrepancy than usual. The individual phases of bismuth have a comparatively small compressibility, the larger part of the changes of volume being contributed by the phase changes, so that less accuracy than usual is to be expected for the compressions of the pure phases. The present compression between 25,000 and 40,000 is 40% greater than the former value; this means, however, a much smaller discrepancy on the total change of volume. For the previously known transition at 45,000 the volume changes 0.005 and 0.007 were found, against the former value 0.0024. The present value is certainly to be preferred because the transition is so near to the end of the former range that it may not have run to completion. For the new transition at 65,000 the two runs gave volume changes of 0.005 and 0.006. At the upper transition at 90,000 the two values were 0.009 and 0.015; this is so near the end of the range that accuracy is reduced. The compressions given in the table between 25,000 and 40,000 were based almost entirely on the new work, disregarding the former. The table lumps together at 25,000 the two transitions I–II and II–III; the transition parameters for these separately are given in the preceding papers.

Selenium is obviously a candidate for a transition because of the known multiplicity of forms at atmospheric pressure. The material was the same as in my previous measurements to 50,000, which I owe to the courtesy of the American Smelting and Refining Co. who had specially purified it. Three set-ups were made with this material; the second set-up gave points with increasing pressure only, the run being terminated by an explosion at the maximum pressure. Selenium is known to be in a state of incomplet internal equilibrium under normal conditions and this was confirmed by the failure of th measurements at high pressure to be reproducible The material originally placed in the piezomete was a shiny black glass, obtained by melting o the original black powder in a pyrex tube with bunsen burner until evolution of gas had ceased and slow cooling. The first run gave a curv with a distinct break in direction at 63,000. Th second run, increasing pressure only, gave large changes of volume than the first, and also th break in direction at 63,000. The third run wa not made with virgin material, as had been th first two, but was with mostly the material fro the second run which had been exposed to 100,00 to which a small amount of virgin material was added to make up the quantity. The compression was markedly smaller than that of the first run, at 100,000 being 0.295 against 0.335. The same break in direction near 60,000 was found with increasing pressure as with the first two, but much less in magnitude, and the break had disappeared with decreasing pressure. It would appear that some permanent change is produced by the application of pressure, although it is too small to show up as a measurable change of volume. Since the compressions between 25,000 and 50,000 of the third run agreed with the previous measurements[13] to better than one per cent, it is the results of the third run which are given in the table. Above 50,000 the present results are a smooth continuation of the previous ones. Attention should be given to the sharp break in direction in the neighborhood of 25,000 found in the previous work, and doubtless connected in some way with the glassy condition. The character of the compression curve of selenium is unlike that of all the other substances of this paper, being characterized by an initial steep rise and then an unusually rapid falling off at the high pressures.

Tellurium has already been investigated[14] to 50,000; at room temperature it has one transition just above 40,000. One new transition was found in the new range, at 70,000, with a volume change only one eighth as large. The material was the same as that used in the previous measurements, purified by the Research Department of the Raritan Copper Works some 17 years ago. The agreement between the two set-ups was not as good as usual in spite of the fact that the friction was no more than usual. At 100,000 the compressions differed from the mean by 4.3%. The volume changes at the low pressure transition were 0.049 and 0.061 against the former value 0.0044. Both the new values are higher than the former one; the new values are doubtless to be preferred because the transition comes so near the end of the previous range that it may not have run to completion. For the high pressure transition the two runs gave for the change of volume 0.004 and 0.010; the mean was used in the table. There is a striking drop in the compressibility on passing through the low pressure transition; this could not be established by the former measurements because the transition is too near the end of the range. On the other hand, there is not much change in compressibility on passing through the high pressure transition.

In addition to the materials listed in the table a great many applications of pressure were made in the preliminary work to lead and to NaCl. It may be stated that neither of these substances has a transition up to 100,000, at least of a magnitude comparable with those listed here.

DISCUSSION

Many of the important points have already been mentioned in the detailed presentation of data. The general shape of the curves of compression against pressure is of interest. This is given crudely by the ratio of the compression at 100,000 to that at 50,000 and is shown in Table II.

TABLE II

Substance	$\frac{\Delta V_{100,000}}{\Delta V_{50,000}}$	$\frac{\Delta V_{50,000}}{\Delta V_{25,000}}$
Li	1.67	1.63
Na	1.42	1.49
K	1.36_5	1.39
Rb	1.38	1.34
Zn	1.76	1.95
Cd	1.63	1.78
In	1.70	1.76
Sn	1.76_5	1.85
As	1.53	1.57_5
Se	1.30	1.33_5

Obviously the ratio has significance only for those substances with no transitions. The ratio of the compression at 100,000 to that at 50,000 is to be compared with the ratio at 50,000 to that at 25,000. The latter should be greater than the former, for obviously if the ratio does not drop with rise of pressure the volume will presently become negative. This expectation is fulfilled in the case of the ten substances for which the ratio has significance because of the absence of transitions, except for lithium and rubidium. In the case of the latter the slight rise in the ratio may possibly be due to error in the low pressure compressions, which are known not to be as accurate as for the other alkali metals. For lithium the absolute values of the volume decrements are small enough so that failure of the condition does not mean the imminence of catastrophe, but it is obvious that there must be some reversal of the trend for lithium at higher pressures. In general, it was a surprise to me that the ratio does not drop more with increasing pressure; this is another way of saying that the compressibility does not drop off with rising pressure as much as I had expected.

The ratios should in general be higher the smaller the absolute values of the compression. That this is true for most substances has been known for a long time[15] in a lower pressure range. However, there are minor exceptions, as shown by the failure of the ratios to lie on a single smooth curve when plotted against the absolute compressions. The accurate fulfillment of any such condition as presupposed in Murnaghan's analysis, for example, would demand a single smooth curve. The most striking exception is, as already mentioned, for selenium.

Another point of interest is the change of compression on passing through a transition. This is given by plotting first differences from the table against pressure. The only cases in which there is any discontinuity in compressibility definitely beyond experimental error are the low pressure transition of tellurium, where the compressibility of the high pressure modification is less than one half that of the low pressure modification, and the transition of calcium, for which the compressibility of the high pressure modification is about two thirds that of the low pressure modification. This is the reverse of the state of affairs that has been found to be generally characteristic of transitions, for in general the compressibility of the high pressure phase is greater than that of the low pressure phase for those transitions investigated over the previous lower pressure ranges. The differences previously found were usually small, however, and would probably be beyond the error of the present measurements.

For the carboloy I am much indebted to the Carboloy Company, and for skillful assistance in constructing the apparatus and setting it up to Mr. Charles Chase. The work received financial support from the Milton Fund of Harvard University, and the Rumford Fund of the American Academy of Arts and Sciences.

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RECORDS OF MEETINGS, 1940–1941, 1941–1942

PRESIDENTS OF THE ACADEMY

OFFICERS AND COMMITTEES FOR 1942–1943

LIST OF THE FELLOWS AND FOREIGN HONORARY MEMBERS

STATUTES AND STANDING VOTES

RUMFORD PREMIUM

PERMANENT SCIENCE FUND

RECORDS OF MEETINGS

One Thousand Two Hundred and Sixty-Fourth Meeting

OCTOBER 9, 1940.—STATED MEETING

The Academy met at its House at 8.20 P. M.

The President in the Chair.

There were present forty-nine Fellows and forty-six guests.

The records of the meeting of May 8 were read and approved.

The Corresponding Secretary reported the receipt of letters accepting Fellowship from Robert Granville Caldwell, Serge Elisséeff, William Lloyd Evans, Lon Louvois Fuller, Harold Locke Hazen, Frederick Vinton Hunt, Werner Wilhelm Jaeger, Henry Tilton Lummus, William de Berniere MacNider, Paul Christoph Mangelsdorf, J. Robert Oppenheimer, Edgar Howard Sturtevant, Donald Dexter Van Slyke, Paul Dudley White, and John Wulff; letters accepting Foreign Honorary Membership from Fernand Baldensperger, Paul Hindemith, Martin Persson Nilsson, and Igor Stravinsky; also of letters declining Fellowship from Henry Bruere, Lloyd Kirkham Garrison, Alvin Saunders Johnson, and Archibald MacLeish.

He also announced that the Council had made the following grants from the income of the Permanent Science Fund.

1. To Lloyd R. Watson, Professor of Chemistry, Alfred University, Alfred, N. Y., for expendable materials and for assistance in a continuation of his study of eye colors of mutant bees, $450.

2. To Edward H. Kemp, Assistant Professor of Psychology, Duke University, for rebuilding an amplifier system to be used in recording impulses from single fibers of the eighth nerve, $250.

3. To Dr. Daniel Abramson, Assistant in Obstetrics, Boston Lying-In Hospital, for chemicals, animals and other expendable materials to be used in a study of the effect of "Relaxin" on smooth muscle, $300.

4. To Lyman G. Parratt, Assistant Professor, Cornell University, for equipment and construction of high voltage apparatus for a continuing study of the outer energy levels of solid materials, $325, contingent upon receipt by the recipient of a similar sum from the Rumford Committee or elsewhere.

To Charles W. Turner, Professor of Dairy Husbandry, University of Missouri, for the purchase of experimental animals and feed for a study of the relation of thyroid gland to the fat, carbohydrate and protein metabolism hormones of the anterior pituitary, $500.

6. To George E. Valley, Jr., National Research Fellow, Harvard University, for machine work, metal stock, materials and specimens required in his study of the energy and relative intensity of gamma rays from certain atomic nuclei, $450.

7. To Donald H. Menzel, Professor of Astrophysics, Harvard University, for the purchase of quartz plates and other materials to construct filters for isolating narrow bands of light to be used in astronomical studies, $450.

8. To Alfred C. Lane, Professor Emeritus of Geology, Tufts College, to supply certain materials and assistance to Professor Wahl, of Helsinki, Finland, as a part of the program of the Committee on the Measurement of Geological Time of the National Research Council, $250, provided that means can be found to forward materials and funds to the above destination.

9. To Alvin L. Moxon, Experiment Station Chemist, South Dakota College, Brookings, for materials and animals to be used in his investigation of the antagonism between arsenic and selenium as it relates to selenium poisoning of livestock, $300.

10. To Martin D. Whitaker, Instructor of Physics, New York University, a final grant for the rental of a radium beryllium source to continue his investigation in slow neutron scattering, which was supported from this fund in the calendar year just completed, $500, contingent upon the applicant's ability to secure $350 from some other source.

11. To Hugh M. Huffman, Assistant Professor of Biochemistry, California Institute of Technology, for construction of a semimicro bomb to be used in his continuing studies of the application of thermodynamics to physiological processes,

$400, contingent upon his assurance that funds will be available for the remainder of the cost of the problem outlined by him.

12. To James A. Beattie, Professor of Physical Chemistry, Massachusetts Institute of Technology, a final grant for materials and construction of a cryostat to cover the temperature range 0° to −270° C. to be used in the absolute temperature scale from −270° to −450° C., $500.

The President then described an expedition undertaken by the Academy and Harvard University in 1780 to observe a total eclipse of the sun from an island in Penobscot Bay, at which time Bailey's beads were first described. He said that the marker on the site needs restoration and that the matter may be referred to the Council of the Academy.

The following communication was presented:

Tenney L. Davis: "The Identity of Chinese and European Alchemical Theory," illustrated with lantern slides.

Dr. J. J. Livingood, of Harvard University, then described the exhibits of the transmutation of the elements, which were on display in the library office.

Two papers were read by title: "Four Hundred Word Chin Tan of Chang Po-Tuan," by Tenney L. Davis and Chao Yün-ts'ung; and "The Scattering of Fast Electrons by Heavy Elements," by J. H. Bartlett and R. E. Watson, presented by E. C. Kemble.

The meeting was dissolved at ten o'clock.

One Thousand Two Hundred and Sixty-Fifth Meeting

NOVEMBER 13, 1940—STATED MEETING

The Academy met at its House at 8.20 P. M.

The President in the Chair.

This having been designated as Ladies' Night, there were present 168 Fellows and guests.

The records of the meeting of October 9 were read and approved.

The Corresponding Secretary reported the receipt of letters accepting Fellowship from Albert Francis Blakeslee and Thomas Head Thomas; and of letters resigning Fellowship from William James and Frederick Albert Saunders.

The following communication was presented:

Edward L. Thorndike: "The Production, Retention and Attraction of Superior Men."

After the meeting Dr. Gregory Pincus, of Clark University, made a demonstration of the physiology of mammalian eggs, exhibiting charts and microphotographs illustrating the development of rabbit ova. Included with the demonstration were microscope exhibits of living rabbit eggs and live rabbits produced parthenogenetically.

The meeting was dissolved at 9.45 P. M.

One Thousand Two Hundred and Sixty-Sixth Meeting

DECEMBER 11, 1940—STATED MEETING

The Academy met at its House at 8.15 P. M.

The President in the Chair.

There were present forty-six Fellows and forty-five guests.

The records of the meeting of November 13 were read and approved.

The following communications were presented:

Fletcher G. Watson: "The Approaching Comet."

James G. Baker: "Trends in Astronomical Optics."

Donald H. Menzel: "Motions in the Solar Atmosphere."

One paper was read by title: "Photographic Evidence on the Visibility of Color Patterns in Butterflies to the Human and Insect Eye," by Charles T. Brues.

The meeting was dissolved at 9.50 P. M.

One Thousand Two Hundred and Sixty-Seventh Meeting

JANUARY 8, 1941—STATED MEETING

The Academy met at its House at 8.25 P. M.

The President in the Chair.

There were present fifty-seven Fellows and forty-four guests.

The records of the meeting of December 11 were read and approved.

The Corresponding Secretary reported the receipt of a letter from Philip Drinker resigning Fellowship.

The following communication was presented:

Thomas H. Thomas: "The Hitler War and Hemisphere Defense."

An exhibit of scale models of ships of the British navy, from the Francis Russell Hart Nautical Museum of the Massachusetts Institute of Technology, was then described by Professor James R. Jack.

The meeting was dissolved at 9.40 P. M.

One Thousand Two Hundred and Sixty-Eighth Meeting

FEBRUARY 12, 1941—STATED MEETING

The Academy met at its House at 8.15 P. M.

Vice-President Wolbach in the Chair.

There were present forty-nine Fellows and thirty-seven guests.

The records of the meeting of January 8 were read and approved.

The following communication was presented:

Harold E. Edgerton: "Stroboscopic Light and its Applications," illustrated with motion pictures.

"An Experiment in Fifteenth Century Typemaking," exhibited on the third floor, from the Dard Hunter Paper Museum of the Massachusetts Institute of Technology, was then described.

The meeting was dissolved at 9.40 P. M.

One Thousand Two Hundred and Sixty-Ninth Meeting

MARCH 12, 1941—STATED MEETING

The Academy met at its House at 8.30 P. M.

The President in the Chair.

There were present thirty Fellows and thirty guests.

The records of the meeting of February 12 were read and approved.

The Corresponding Secretary announced that the Council had approved the recommendation of the Rumford Committee that the Rumford Premium be awarded to Vladimir K. Zworykin, of Camden, N. J.

He also announced that the Council had made the following grants from the Permanent Science Fund:

1. To Robert B. Dean, Junior Instructor, University of Minnesota, for the study of bimolecular films, $200.

2. To Dr. Nicholas T. Werthessen, Endocrine Laboratory, Boston Dispensary, for assistance in the study of ovarian disfunctions, $720.

3. To Graham P. DuShane, Instructor in Zoology, University of Chicago, for assistance in the investigation of reflexes through isolated motor cells, $400.

4. To Donald D. Brand, Professor of Anthropogeography, University of New Mexico, for materials and field expenses of an archeologic study of the occupation sequence in the middle Rio Balsas area, Guerrero and Michoacan, Mexico, $405.

5. To Charles B. Davenport, formerly of the Carnegie Institution, Cold Spring Harbor, N. Y., for assistance in completing the analysis of certain biometrical studies on children, $200.

6. To Joseph S. Butts, Professor of Biochemistry, Oregon State College, for expendable materials and for assistance in continuing his study of the intermediary metabolism of amino acids, $350.

7. To Paul A. Vestal, Research Curator, Botanical Museum, Harvard University, for expendable materials, assistance, and certain field expenses, in connection with an ethnologic study in the economic botany of the Ramah-Atarque Navaho Indians, $300.

8. To George W. Kidder, Assistant Professor of Biology, Brown University, for assistance in studies of substances produced by living cells which accelerate or inhibit the proliferation of other cells, $450.

9. To Barry Commoner, Tutor, Department of Biology, Queens College, Flushing, N. Y., for equipment to permit continuation of a biochemical investigation of the relation between auxin, respiratory mechanisms, and growth in plant cells, $350.

10. To Vincent G. Dethier, Instructor in Biology, John Carroll University, Cleveland, Ohio, toward expenses of a study of the chemistry of food plants chosen by larvae of certain species of Chrysophanus in North America, $200.

11. To Margaret Harwood, Director, Maria Mitchell Observatory, Nantucket, Mass., for assistance in a study of the form and motions of Eros, $400.

12. To Frederick Johnson, Curator, Robert S. Peabody Foundation for Archæology, Andover, Mass., toward the cost of publication of the data from collaborative studies upon the Boylston Street Fishweir, $300.

13. To Philip M. Morse and Julius A. Stratton, Professor and Associate Professor of Physics, respectively, the Massachusetts Institute of Technology, for assistance in completing the calculation of tables of functions involved in the theory of wave radiation and scattering, $450.

14. To Leigh Hoadley, Professor of Zoology, Harvard University, for assistance in the study

of nerve processes arising from isolated portions of the embryonic brain, and the differentiated tissues into which the processes lead, $150.

On the recommendation of the Council the Academy voted the following appropriations for the year ending March 31, 1942:

From the income of the General Fund, $7,000, to be used as follows:

for House expenses	$2,000
for General and Meeting expenses	800
for Library expenses (salaries, periodicals, binding)	3,200
for Treasurer's expenses	900
for President's expenses	100
	$7,000

From the income of the Publication Funds, $2,350, to be used for publication.

From the income of the Rumford Fund, $3,000, to be used at the discretion of the Committee.

From the income of the C. M. Warren Fund, $1,000, to be used at the discretion of the Committee.

The President appointed the Nominating Committee, as follows:

Otto Oldenberg, of Class I
Roy G. Hoskins, of Class II
Ralph E. Freeman, of Class III
Ernest F. Langley, of Class IV

Dr. Viets reported the destruction by bombs of the library and collections of the Manchester (Eng.) Literary and Philosophical Society, and it was suggested that this Academy might be able to reproduce by microphotography some of the Society's publications from the files in the Academy's library.

The following communication was presented:

Sir Herbert Brown Ames, K. B.: "Canada's Major Contribution in the Present War."

Mr. Robert Gray, of the Dewey and Almy Chemical Company, Cambridge, then described an exhibit of balloons used in high altitude atmospheric exploration.

The meeting was dissolved at 10.15 P. M.

One Thousand Two Hundred and Seventieth Meeting

APRIL 9, 1941—STATED MEETING

The Academy met at its House at 8.15 P. M.

Vice-President Pease in the Chair.

There were present thirty-five Fellows and twenty-six guests.

The records of the meeting of March 12 were read and approved.

The Corresponding Secretary reported the receipt of a letter from Cyrus E. Dallin resigning Fellowship.

The following communication was presented:

Kenneth J. Conant: "The Architectural Revolution: an Historical Background for the New Architecture in America."

Dr. Kenneth V. Thimann presented a demonstration concerned with the control of growth in plants by hormones.

The meeting was dissolved at 10 P. M.

One Thousand Two Hundred and Seventy-First Meeting

MAY 14, 1941—ANNUAL MEETING

The Academy met at its House at 8.20 P. M.

The President in the Chair.

There were present fifty-three Fellows and thirty-four guests.

The records of the meeting of April 9 were read and approved.

The Corresponding Secretary announced that the following had been elected members of the Academy:

FELLOWS

CLASS I

Section 1. Fred Lawrence Whipple, Cambridge
Section 2. Isidor Isaac Rabi, New York, N. Y.
Section 3. George Whiteley Coggeshall, Cambridge
Charles Edward Kenneth Mees, Rochester, N. Y.
Harry Boyer Weiser, Houston, Texas.
Ralph Chillingworth Young, Arlington
Section 4. Edward Lindley Bowles, Wellesley
Charles Stark Draper, Newton
Reinhold Rüdenberg, Belmont
Vladimir Kosma Zworykin, Camden, N. J.

CLASS II

Section 1. Alan Mara Bateman, New Haven, Conn.
Chester Stock, Pasadena, Cal.

Section 2. Arthur Johnson Eames, Ithaca, N. Y.
Section 3. Francis Otto Schmitt, St. Louis, Mo.
Section 4. Fuller Albright, Brookline
Walter Bauer, Waban
Alan Richards Moritz, Waban

Class III

Section 1. Erwin Nathaniel Griswold, Belmont
Section 2. Hajo Holborn, New Haven, Conn.
Gaetano Salvemini, Cambridge
A. Eugene Staley, Medford
Section 3. Carl Rupp Doering, Cambridge
Earl Jefferson Hamilton, Durham, N. C.
Francis Trow Spaulding, Cambridge
Robert Ulich, Cambridge
Section 4. Godfrey Lowell Cabot, Boston
Frederic Adrian Delano, Washington, D. C.
Edward Godfrey Huber, Waban
Laurence Leathe Winship, South Sudbury

Class IV

Section 1. James Bissett Pratt, Williamstown
Section 2. Warren Ortman Ault, Waban
William E. Lingelbach, Philadelphia, Pa.
Section 3. Giuseppe Antonio Borgese, Chicago, Ill.
Section 4. Archibald Thompson Davison, Lincoln
Walter Hamor Piston, Jr., Belmont

FOREIGN HONORARY MEMBERS

Class II

Section 3. Bernado Alberto Houssay, Buenos Aires, Argentina

Class IV

Section 4. Jan Sibelius, Helsinki, Finland

The annual reports of the Council, the Treasurer, and the standing committees were accepted and placed on file, as follows:

REPORT OF THE COUNCIL

Since the last report there have been reported the deaths of twenty-one Fellows: Charles Value Chapin, Worthington Chauncey Ford, Louis John Gillespie, Robert Grant, William Caspar Graustein, William Arthur Heidel, Samuel Henshaw, Charles Clifford Hutchins, Matt Bushnell Jones, Charles Rockwell Lanman, Frederick Lawton, Dayton Clarence Miller, James Madison Morton, James Flack Norris, Raymond Pearl, George Rutledge, Charles Wardell Stiles, Frank William Taussig, Eugene Wambaugh, John Eliot Wolff, Hans Zinsser; and four Foreign Honorary Members: Henri Louis Bergson, Sir Albert Charles Seward, Josiah Charles Stamp, Baron Stamp, Sir Joseph John Thomson.

Twenty-four Fellows and four Foreign Honorary Members were elected by the Council and announced to the Academy at its annual meeting in May 1940.

The roll now includes 765 Fellows and 125 Foreign Honorary Members (not including those elected in May 1941).

Treasurer's Report

Operating Receipts

Income from Investments (Schedule D)		$12,941.09	
Unappropriated Income 1940, Transferred			
Warren Fund	$22.66		
Publication Funds	39.91		
		62.57	
Total Income to Funds (Schedule G)			$13,003.66
Income from Trustees Permanent Science Fund			12,181.18
Assessments and Admissions			4,110.00
Mabel S. Agassiz Fund, Gift			2,000.00
Sale of Publications			497.24
American Council of Learned Societies, for Lake Fund			1,500.00
Lake Publication Fund Subscriptions			387.45
Balance of Rumford Fund Grant, Returned			145.33
Anonymous Contribution			2,500.00
Appropriations from Current Expense Fund:			
General Academy Expenses, Deficit		$268.21	
Special Academy Expenses:			
Repairs	$851.41		
Policy Committee	212.50		
		1,063.91	
			1,332.12
Total Receipts			$37,656.98

OPERATING EXPENDITURES

Academy, General:			
Library, Salaries	$2,078.00		
Books and Binding	924.54		
		$3,002.54	
General (Net)		1,370.06	
House (Net)		2,074.10	
President's Office		40.50	
Treasurer's Office		869.35	
Total		$7,356.55	
Amory Fund:			
Expense		62.35	
Special, Recording Secretary:			
Salaries and Expenses		1,606.29	
Publication Committee:			
General	$5,688.18		
Lake	2,395.49		
Hatch	46.18		
		8,129.85	
Rumford Fund:			
Grants	$2,160.00		
Miscellaneous	4.50		
		2,164.50	
Warren Fund:			
Grant	$280.00		
Balance of Income to Fund	643.53		
		923.53	
Permanent Science Fund:			
Grants	$10,055.00		
Expense	20.48		
		10,075.48	
Total (Schedule F)			$30,318.55

SPECIAL EXPENDITURES

Current Expense Fund:			
Building & Equipment Repairs	$851.41		
Policy Committee	212.50		
		$1,063.91	
Mabel S. Agassiz Fund:			
For Meetings		110.20	
			1,174.11
Total Expenditures			$31,492.66
Excess Receipts			6,164.32
Total to Balance			$37,656.98

REPORT OF THE LIBRARY COMMITTEE

During the year 1940–41, 109 volumes and 14 unbound numbers of serials were borrowed by nine Fellows and 16 libraries, and many more have been consulted at the Academy.

The number of volumes on the shelves at the time of the last report was 46,341. During the year 348 volumes were added, making the number now 46,689. Of this number 321 were received by gift or exchange and 27 were purchased.

The appropriation for the year ending March 31, 1941, was $3,300, and the expenditures were as follows:

Salaries	$2,078.00
Purchase of Books and Periodicals	389.34
Binding	535.20
Total	$3,002.54

The exchange of publications with foreign institutions has naturally been much affected by the European war. The number received by us has been greatly reduced, and the Academy, though continuing to mail its publications to foreign subscribers, has not sent any by the International Exchange Service later than no. 4, of vol. 73 of its Proceedings.

Respectfully submitted,
HERVEY W. SHIMER, *Librarian*

May 14, 1941.

REPORT OF THE RUMFORD COMMITTEE

Between April 1st, 1940 and April 9th, 1941 the following grants were made:

April 23, 1940		
No. 356	To Dr. Donald H. Menzel to aid in a quantitative determination of the chemical composition of the solar atmosphere.	$275
May 6, 1940		
No. 357	To Professor Frank Schlesinger to aid in the installation of an electron multiplier for use in the determination of stellar magnitudes.	150
October 9, 1940		
No. 358	To Dr. Lyman G. Parratt to aid in X-ray spectroscopic studies of the solid state.	325
No. 359	To Dr. E. J. Schremp for continuance of an experimental research program in cosmic rays.	400
December 23, 1940		
No. 360	To Professor Wilson M. Powell for projected cosmic ray researches on Mount Evans.	250
No. 361	To Dr. John W. Evans in aid of researches on the solar surface.	310
January 29, 1941		
No. 362	To Professor Charles F. Brooks for the construction of a sensitive radiometer for the measurement of long-wave atmospheric radiation.	$300

April 9, 1941

No. 363	To Dr. A. H. Pfund for the construction of a modern infrared spectroscope to be used by him and his students for pure research.	400
No. 364	To Professor J. R. Roebuck to aid him in his work on the Joule-Thomson effect.	200
No. 365	To Dr. E. P. Little for the measurement of the optical properties of various metals in the Schumann region.	280

Letters were sent to nine recipients of grants made between October 2, 1939, and October 9, 1940. Replies were received from all grantees and considerable progress was reported.

The Committee submitted to the Council the name of Dr. Vladimir Kosma Zworykin as Rumford medalist, the medals being awarded for his invention of the iconoscope and other television devices.

Respectfully submitted,
NORTON ADAMS KENT,
Chairman

May 14, 1941.

REPORT OF THE C. M. WARREN COMMITTEE

The Committee had at its disposal during the fiscal year, 1940–41, the sum of $870.

Since the last annual report the following grant has been made:

To Professor E. C. Gilbert of Oregon State College, $280 to be used to cover the cost of apparatus necessary for his work on the heat of combustion of the heptanes.

On account of the small return from the endowment of the Fund, it was voted to return to the Treasurer the excess of the money available this year over the $280 above noted, to be added to the principal.

Reports of progress have been received from Messrs. Amdur, Gilbert and Huntress.

A reprint has been received on research aided by the Warren Fund, namely:

"Identification of Organic Compounds. II. Piperidyl Derivatives of Aromatic Halogenonitro Compounds." Margaret K. Seikel. J. Am. Chem. Soc. *62*, 750 (1940).

Respectfully submitted,
FREDERICK G. KEYES,
Chairman

May 14, 1941.

REPORT OF THE COMMITTEE OF PUBLICATION

The Committee has held four meetings during the year, two of which were quite protracted, and work of the Committee was greatly facilitated by the fact that the President and the Treasurer agreed in recommending to the Council that an appropriation of $200 be made available to the Chairman for secretarial expenses. In this connection, the Chairman wishes to express in behalf of himself and the Committee his thanks to the Council.

During the year a considerable body of papers were published (fifteen all told) comprising numbers 8–15 of volume 73 and 1–7 of volume 74. It should be noted that in all cases these papers had been accepted during the previous years, and that no new papers were published.

The Chairman regrets to report that the publication appropriation was overdrawn by $215.91. This was primarily due to an error on his part in not distinguishing between general and restricted funds and also to the fact that the *Records Number* was considerably larger than had been estimated, owing to the fact that it covered two years of the Academy's activities and contained a large number of biographical memoirs, two of which were of very considerable length.

With regard to Professor Lake's publication of *Dated Greek Manuscripts*, it was agreed that, in view of present conditions, the publication of a final fascicule comprising manuscripts from Sinai, Spain and some other scattered material, would have to be deferred, and it was advisable to proceed with the preparation of the Index on the basis of the material already published. Professor and Mrs. Lake are now at work on this, and specimen pages are awaited shortly.

With regard to Professor Hatch's publication, *An Album of Dated Syriac Manuscripts*, it seemed inadvisable, under war conditions, to continue the plan of publication with the Oxford University Press which had been previously adopted. Your Committee, feeling that a decision of this importance should be taken by the Council, submitted a memorandum on the matter to that body, and the manuscript was withdrawn from the Oxford Press. It has now become possible to obtain an adequate supply of Syriac characters in America, and negotiations have been opened for its publication here. The plates are being prepared by the Meriden Gravure Company, and final blueprints of them are in the hands of the author and the editor. The printing will be carried out by the J. H. Furst Company of Baltimore, but it will probably be necessary to defer completion of this work for some months in view of the inadequacy of the funds now available.

A study has been initiated of the Academy's publications over the last ten years, with a view to establishing a normal estimated page cost of different types of scientific work and of analyzing the amount of publication in various scientific fields so as to bring about a more rounded series of publications by the Academy.

The income for the year was $5,472.27. There was expended $5,688.18, forming an overdraft of $215.91, as noted above. The estimated income for the year 1941–42 has been fixed at $2,350.

The Chairman has no general recommendations to make apart from the following:

It seems advisable, where mathematical papers are concerned, to have them printed in the *Memoirs*, where the different format is advantageous.

Respectfully submitted,
ROBERT P. BLAKE,
Chairman

May 14, 1941.

REPORT OF THE HOUSE COMMITTEE

During the year 1940–41 the House Committee has had at its disposal funds amounting to $2,199.60, made up as follows:

Appropriation for 1940–41	$2,000.00
Received from other societies for the use of rooms	199.60
Total	$2,199.60

The expenditures amounted to $2,273.70, a detailed list of which follows:

Janitor	$962.00
Electricity: Light	190.71
Power	53.82
Fuel	714.47
Elevator	60.00
Telephone	114.99
Gas	46.94
Water	34.96
Upkeep	61.32
Janitor's supplies and sundries	34.49
Total	$2,273.70

During the summer of 1940, $562 was spent for building repairs, chiefly to the roof, and $289.41 for the cleaning and repair of rugs, draperies and furniture. These items were not included in the House account figures, since they were paid for from the Current Expense Fund.

Meetings have been held as follows:

The Academy: Stated meetings	8
Conferences on Science and Values	7
Boston Surgical Society	3
Bureau of University Travel	3
Emergency Rescue Committee	1
Geological Society of Boston	2
New England Botanical Club	9
Total	33

The Council Chamber has been used for the Academy Council and Committee meetings, and also by the Trustees of the Children's Museum and the Farm and Garden Association.

Respectfully submitted,
E. F. LANGLEY, *Chairman*

May 14, 1941.

It was *Voted*, to amend Chapter XI, Article 2, Section x, of the Statutes, as follows:

The first paragraph shall be amended by striking out the word "notices" and inserting "records." The paragraph shall be further amended by adding after "Fellows" the words "and Foreign Honorary Members."

The second paragraph shall be omitted in its entirety.

It was *Voted*, to confirm the award already made by the Council of the Rumford Medal to Vladimir Kosma Zworykin, of Camden, N. J., for his invention of the iconoscope and other television devices.

It was *Voted*, that the annual assessment for the ensuing year shall be ten dollars for Fellows living within fifty miles of Boston.

The following officers and committees were elected for 1941–1942:

HARLOW SHAPLEY, *President*
PERCY W. BRIDGMAN, *Vice-President for Class I*
S. BURT WOLBACH, *Vice-President for Class II*
SIDNEY B. FAY, *Vice-President for Class III*
FRED N. ROBINSON, *Vice-President for Class IV*
ABBOTT P. USHER, *Corresponding Secretary*
HUDSON HOAGLAND, *Recording Secretary*
HORACE S. FORD, *Treasurer*

Frederick H. Pratt, *Librarian*
Robert P. Blake, *Editor*

Councillors for Four Years:

Norton A. Kent, for Class I
David Rapport, for Class II
Edward H. Chamberlin, for Class III
Samuel H. Cross, for Class IV

Committee on Policy and Resources:

Henry S. Dennison, *Chairman*
Dugald C. Jackson, *Member for Five Years*

Finance Committee:

Alfred L. Ripley
John F. Ebersole
Ralph E. Freeman
Henry P. Kendall

Rumford Committee:

Norton A. Kent, *Chairman*
Percy W. Bridgman
Harry M. Goodwin
Harlow Shapley
George R. Harrison
Robert B. Lindsay
George W. Pierce

C. M. Warren Committee:

Frederick G. Keyes, *Chairman*
Gregory P. Baxter
Walter L. Jennings
Tenney L. Davis
Charles A. Kraus
Reid Hunt
Grinnell Jones

Committee of Publication:

Robert P. Blake, *Chairman*
Edwin C. Kemble, of Class I
Ralph H. Wetmore, of Class II
Joseph H. Beale, of Class III
Robert P. Casey, of Class IV

Committee on the Library:

Frederick H. Pratt, *Chairman*
Raymond C. Archibald, of Class I
Thomas Barbour, of Class II
Nathan Isaacs, of Class III
Henry B. Washburn, of Class IV

Auditing Committee:

George R. Agassiz
Alexander Forbes

House Committee:

Ernest F. Langley, *Chairman*
H. Addington Bruce
Robert P. Bigelow
Walter E. Clark

Committee on Biographical Notices:
For Three years:

J. Seeley Bixler, *Chairman*
Hudson Hoagland

Committee on Meetings:

The President
The Recording Secretary
Leonard Carmichael
Samuel H. Cross
Tenney L. Davis
Soma Weiss

This year for the first time the Francis Amory septennial prize was awarded, the sum of $17,000 being divided equally between four individuals, and at this meeting the presentation was made to the three American winners. The fourth winner is a European scientist in a country unhappily dominated by Nazi invaders. His name will not now be made public and his prize will be held here in trust.

Each of the three recipients was presented to the Academy by a member of the Committee on the Francis Amory Fund: Dr. Hugh H. Young, by Dr. William C. Quinby; Dr. Joseph F. McCarthy, by Dr. David Cheever; and Dr. Carl Richard Moore, by Dr. Leigh Hoadley.

They then addressed the Academy, describing their investigations, placing special emphasis on the circumstances leading to the culmination of the work for which the prize was given.

The meeting was dissolved at 10.45 P. M.

One Thousand Two Hundred and Seventy-Second Meeting

October 8, 1941—Stated Meeting

The Academy met at its House at 8.15 P. M.

The President in the Chair.

There were present 83 Fellows, one Foreign Honorary Member, and 53 guests.

The records of the meeting of May 14 were read and approved.

The Corresponding Secretary reported the receipt of letters accepting Fellowship from Fuller Albright, Warren Ortman Ault, Alan Mara Bateman, Walter Bauer, Giuseppe Antonio Borgese, Edward Lindley Bowles, Godfrey Lowell Cabot, George Whiteley Coggeshall, Archibald Thompson Davison, Frederic Adrian Delano, Carl Rupp Doering, Charles Stark Draper, Arthur Johnson Eames, Erwin Nathaniel Griswold, Earl Jefferson Hamilton, Hajo Holborn, Edward Godfrey

Huber, William E. Lingelbach, Charles Edward Kenneth Mees, Alan Richards Moritz, Walter Hamor Piston, Jr., James Bissett Pratt, Isidor Isaac Rabi, Reinhold Rüdenberg, Gaetano Salvemini, Francis Otto Schmitt, Francis Trow Spaulding, Chester Stock, Robert Ulich, Harry Boyer Weiser, Fred Lawrence Whipple, Ralph Chillingworth Young, and Vladimir Kosma Zworykin; and a letter accepting Foreign Honorary Membership from Bernado Alberto Houssay; also a letter declining Fellowship from A. Eugene Staley.

The Corresponding Secretary announced that the Council had made the following grants from the Permanent Science Fund, on the recommendation of the Committee on the Permanent Science Fund:

1. To Warren Andrew, Assistant Professor of Histology and Embryology, Baylor University, for animals and expendable materials, and for assistance in the study of senile changes in mammals, $300.

2. To Forrest F. Cleveland, Associate Professor of Physics, Illinois Institute of Technology, toward the purchase of specified optical equipment, for use in an investigation of Raman spectra of gases and vapors, contingent upon his securing a like sum from other sources, $500.

3. To Rita Guttman, Instructor, Brooklyn College, for equipment and expendable materials for continuing a study of electrical rectification in single nerve fibers, $200.

4. To Rudolf Höber, Visiting Professor of Physiology, University of Pennsylvania, for assistance in a study of molecular configurations and the transport of organic molecules across secretory cells, $600.

5. To Lewis H. Kleinholz, Instructor, Cambridge Junior College, for animals and materials for use in a study of hormonal factors in ecdysis of crustacea, $200.

6. To Irvin M. Korr, Instructor, New York University, for purchase of special differential manometers and vessels for use in a study of carbohydrate metabolism in resting and active tissues, $232.50.

7. To Valy Menkin, Assistant Professor of Pathology, Harvard Medical School, for animals, materials, and assistance in the study of diabetes and inflammation, $600.

8. To George Howard Parker, Professor of Zoology, Emeritus, Harvard University, for expendable materials in a study of the action of neurohumors upon melanophores of the catfish, the eel, and the killifish, $150.

9. To Edward J. Schremp, Assistant Professor, University of Cincinnati, for assistance in a continuing cosmic-ray research program, $350.

10. To Charles W. Turner, Professor of Dairy Husbandry, University of Missouri, for purchase of animals for a continuing study of thyroid and pituitary hormone interrelations, $300.

11. To Clarence Zener and Kenneth Fitzsimmons, Associate Professor and Instructor, respectively, State College of Washington, for construction of apparatus for use in the study of elastic after-effect in cold worked metals, $400.

Professor Norton A. Kent, chairman of the Rumford Committee, introduced Dr. Vladimir K. Zworykin as the Rumford medalist of 1941 for his invention of the iconoscope and other television devices, and the President presented the medals to him.

Dr. Zworykin then spoke on "The Electron Microscope."

Two papers were presented by title: "Pressure-Volume Relations for Seventeen Elements to 100,000 kg/cm^2," by P. W. Bridgman; "The Lower Permian Insects of Kansas. Part 9," by F. M. Carpenter.

The meeting was dissolved at 10.05 P. M.

One Thousand Two Hundred and Seventy-Third Meeting

NOVEMBER 12, 1941—STATED MEETING

The Academy met at its House at 8.20 P. M.

The President in the Chair.

There were present seventy-six Fellows, one Foreign Honorary Member and thirty-eight guests.

The records of the meeting of October 8 were read and approved.

The Corresponding Secretary reported the receipt of a letter from Laurence Leathe Winship accepting his election as a Fellow; also letters from Walter R. Spalding and Donald D. Van Slyke resigning Fellowship.

The President announced that the general subject of the monthly meetings of the Academy for the remainder of the Academic year will be the Analysis of Post-War Problems and Procedures, and that special meetings for informal discussion will be held on the Monday evenings following the stated meetings.

The following communication was presented:

Alfred North Whitehead: "Statesmanship and Specialized Learning."

Professor Harry Berman, Curator of the Mineralogical Museum of Harvard University, then described the exhibit of gems and gem minerals which was on view in the Reading Room.

One paper was read by title: "Freezing Parameters and Compressions of 21 Substances to 50,000 kg/sq. cm^2," by P. W. Bridgman.

The meeting was dissolved at 9.15 P. M.

One Thousand Two Hundred and Seventy-Fourth Meeting

DECEMBER 10, 1941—STATED MEETING

The Academy met at its House at 8.21 P. M.

The President in the Chair.

There were present seventy-three Fellows and fifty-four guests.

The records of the meeting of November 12 were read and approved.

The following communications were presented:

Igor I. Sikorsky: "Direct Lift Aircraft in War and Peace," with motion picture illustrations.

Walter S. Lemmon: "Radio as a New Force in the Post War World."

Professor Robert H. Pfeiffer then described a special exhibit of inscriptions and other objects excavated at Nuzi (near Kirkuk, Iraq), dating from the period 2500–1500 B. C.

Two papers were read by title: "The Approximate Solution of Singular Equations Arising in Engineering Practice," by Francis R. Hildebrand, presented by E. C. Kemble and J. H. Van Vleck; "The Inner Chapters of Pao-p'u-tzŭ," by Tenney L. Davis and Ch'ên Kuo-fu.

The meeting was dissolved at 10.10 P. M.

One Thousand Two Hundred and Seventy-Fifth Meeting

JANUARY 14, 1942—STATED MEETING

The Academy met at its House at 8.30 P. M.

The President in the Chair.

This meeting had been designated as Ladies' Night, and there were present about 200 Fellows and their guests.

The records of the meeting of December 10 were read and approved.

The following communication was presented:

Zechariah Chafee, Jr.: "International Utopias."

Dr. Reginald Fitz then described an exhibit of letters and an unpublished manuscript of Dr. Benjamin Waterhouse (1754–1846). This manuscript (the property of the Academy) is a paper entitled "Observations on Epidemic Diseases," which was read at the 13th meeting of the Academy, on May 27, 1783, and it was

Voted that the paper should now be published.

The meeting was dissolved at 10.15 P. M.

One Thousand Two Hundred and Seventy-Sixth Meeting

FEBRUARY 11, 1942—STATED MEETING

The Academy met at its House at 8.25 P. M.

Vice-President Fay in the Chair.

There were present fifty-eight Fellows and twenty-three guests.

The records of the meeting of January 14 were read and approved.

The following communications were presented:

Clarence F. Jones: "South America and the War."

Samuel Van Valkenburg: "The Importance of the Netherlands East Indies."

Mr. Eric Schroeder then described a special exhibit of Persian book art.

The meeting was dissolved at 10.15 P. M.

One Thousand Two Hundred and Seventy-Seventh Meeting

MARCH 11, 1942—STATED MEETING

The Academy met at its House at 8.30 P. M.

The President in the Chair.

There were present thirty-seven Fellows, one Foreign Honorary Member and twenty-four guests.

The records of the meeting of February 11 were read and approved.

The Corresponding Secretary announced that the Council had made the following grants from the Permanent Science Fund:

1. To Elso S. Barghoorn, Jr., Instructor in Biology, Amherst College, for miscellaneous expenses of field work and laboratory study of the structural changes in submerged wood and plant remains, $335.

2. To Thomas H. Bissonnette, Professor of Biology, Trinity College, Hartford, Conn., for expendable materials and assistance in a further study of photoperiodicity in animals, $400.

3. To Bart J. Bok, Associate Professor of Astronomy, Harvard University, for the construction of a 26-inch circular mosaic grating to be used with a 24-inch Schmidt telescope, a joint project in collaboration with Dr. R. W. Wood, of Johns Hopkins University, $750.

4. To Vernon I. Cheadle, Assistant Professor of Botany, Rhode Island State College, for assistance in continuing a study of the conducting systems of the Monocotyledoneae, $350.

5. To Clark Goodman, Research Associate, Massachusetts Institute of Technology, for construction of equipment to be used in continuation of a study of the locus and relative concentration of elements in ores by the use of induced radioactivity, $650.

6. To Cornelius S. Hurlbut, Jr., Associate Professor of Mineralogy, Harvard University, for construction of equipment to be used in a study of refractive indices of amphibole and other minerals, $450.

7. To Fred M. Uber, Assistant Professor of Physics, University of Missouri, for reagents for use in a study of synthesis of kojic acid by microorganisms using C^{13} as a tracer, $425.

On the recommendation of the Council the following appropriations were voted for the year 1942–1943:

From the income of the General Fund, $7,000, to be used as follows:

for House expenses	$2,000
for General and Meeting expenses	1,000
for Library expenses	3,000
for Treasurer's expenses	900
for President's expenses	100
	$7,000

From the income of the Publication Funds, $2,000, to be used for publication.

From the income of the Rumford Fund, $3,000, to be used at the discretion of the Committee.

From the income of the C. M. Warren Fund, $875, to be used at the discretion of the Committee.

The President announced the appointment of the Nominating Committee:

George R. Agassiz, of Class I
Warren J. Mead, of Class II
Austin W. Scott, of Class III
Michael J. Ahern, of Class IV, *Chairman*.

The Symposium on Anthropology and World Equilibrium consisted of papers by the following:

1. Carleton S. Coon: "Systems of Human Relations."
2. Conrad M. Arensberg: "Nature of World Equilibrium."
3. Eliot D. Chapple: "How a World Equilibrium Can be Organized."

As Dr. Arensberg was unable to be present, his paper was read by the Recording Secretary.

Following the symposium, Dr. Clark Goodman presented a demonstration of neutron activation of minerals.

The meeting was dissolved at 10.15 P. M.

One Thousand Two Hundred and Seventy-Eighth Meeting

APRIL 8, 1942—STATED MEETING

The Academy met at its House at 8.30 P. M.

The President in the Chair.

There were present thirty-eight Fellows and thirty-four guests.

The records of the meeting of March 11 were read and approved.

The President announced plans to publish in the Academy's Proceedings the papers on post war problems and procedures which have been read at the meetings this year.

The following communication was presented:

A. Warren Stearns: "Psychiatry and the Structure of Society."

Mr. Henry Bradford Washburn, Jr. demonstrated two large aerial cameras and described how they are operated for both vertical mapping and pictorial photography from the air.

The President described some Mexican stamps issued to commemorate the establishment of the new Mexican National Astrophysical Observatory.

The meeting was dissolved at 10.10 P. M.

One Thousand Two Hundred and Seventy-Ninth Meeting

MAY 13, 1942—ANNUAL MEETING

The Academy met at its House at 8.20 P. M.

The President in the Chair.

There were present thirty-one Fellows and eighteen guests.

The records of the meeting of April 8 were read and approved.

The Corresponding Secretary reported that the

Council recommended an amendment to Chapter II, Article 2, of the Statutes, to be acted on by the Academy at some future meeting. This new paragraph would read as follows:

"Members of the Academy on retiring from their academic or other regular duties may, if they so desire and with the approval of the Council, be transferred to the status of Fellows Emeriti. Fellows Emeriti shall be exempt from the payment of dues and may not hold office in the Academy, but shall have all the other privileges of Fellowship. In the published lists of the membership of the Academy, Fellows Emeriti shall be separately classified, and shall be outside the statutory limit set on the number of Fellows."

The annual report of the Council was presented:

REPORT OF THE COUNCIL

Since the last report of the Council the deaths of seventeen Fellows have been reported: Joseph Charles Arthur, Henry Wolf Biklé, Carleton Brown, Philip Cabot, Raymond Dodge, Charles Downer Hazen, Lawrence Joseph Henderson, Eugene Xavier Louis Henry Hyvernat, Nathan Isaacs, Frederick John Foakes Jackson, George Lyman Kittredge, Kurt Koffka, William Lawrence, Frank Burr Mallory, William Albert Noyes, Charles Henry Taylor, Soma Weiss; and of five Foreign Honorary Members: Tullio Levi-Civita, Friedrich von Müller, Charles Émile Picard, Werner Sombart, Hans Spemann.

Thirty-five Fellows and two Foreign Honorary Members were elected by the Council and announced to the Academy in May 1941.

The roll now includes 779 Fellows and 122 Foreign Honorary Members (not including those elected in May 1942).

The Treasurer's report was read of which the following is an abstract:

TREASURER'S REPORT

*RECEIPTS

Academy, General:			
From: Investment Income (Schedule D)	$12,381.82		
Less: Income to Special Funds	9,463.58		
		$2,918.24	
Assessments and Admission Fees		4,345.00	
			$7,263.24
Amory Fund Committee:			
From: Investment Income			$2,943.36
Publications Committee:			
From: Investment Income Appropriation		$2,350.00	
Contribution		5.00	
Sale of Publications		184.85	
American Council of Learned Societies, Hatch Fund		1,168.00	
Subscriptions, Lake Publication		149.75	
			3,857.60
Rumford Fund Committee:			
From: Investment Income			3,002.02
Warren Fund Committee:			
From: Investment Income Appropriation			1,000.00
Mabel S. Agassiz Fund:			
From: Investment Income			109.20
Permanent Science Fund:			
From: Boston Safe Deposit & Trust Co., Trustee		$7,220.96	
Return of Grant (temporary)		200.00	
			7,420.96
Kennelly Fund:			
From: Investment Income			59.00
Investment Reserve Fund:			
From: Final Liquidation Payment on Security held			126.72
Total Receipts			$25,782.10

†EXPENDITURES

Academy, General:			
Library, Salaries	$2,072.00		
Books & Binding	622.00		
		$2,694.00	
General (Net)		1,191.59	
House (Net)		2,225.81	
President's Office		59.50	
Treasurer's Office		514.87	
Insurance		519.10	
			$7,204.87
Amory Fund:			
Grants (Septennial Prizes)		‡$17,200.00	
Expense		192.99	
			17,392.99
Publications Committee:			
General		$1,732.24	
Lake		172.00	
Hatch		2,162.20	
			4,066.44
Rumford Fund Committee:			
Grants		$2,730.00	
Medals		333.15	
			3,063.15

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* Excluding sales of securities.

† Excluding purchases of securities.

‡ $4,300 Grant deferred.

Warren Fund Committee:			
Grants			$975.00
Mabel S. Agassiz Fund:			
For Meetings			109.20
Permanent Science Fund:			
Grants		$8,162.50	
Expense		28.46	
			8,190.96
Special Expense:			
Rec. Secretary	$754.28		
Less Credit	340.75		
		$413.53	
President's Special Fund		100.00	
Current Expense Fund:			
Building & Equipment Repairs	$165.72		
Policy Com.	340.75		
		506.47	
			1,020.00
Total Expenditures			$42,022.61

The annual reports of the standing committees were presented:

REPORT OF THE LIBRARY COMMITTEE

During the year 95 volumes and 23 unbound numbers of serials were borrowed by 10 Fellows and 20 libraries, and many more were consulted at the Academy.

The number of volumes on the shelves at the time of the last report was 46,689. Since then 208 volumes have been added, making the number now 46,897. Of the additions 179 were received by gift or exchange, and 29 were purchased.

The appropriation for the year ending March 31, 1942, was $3,200, and the expenditure was as follows:

Salaries	$2,072.00
Purchase of books and periodicals	196.50
Binding	425.50
Total	$2,694.00

Respectfully submitted,
FREDERICK H. PRATT,
Librarian

May 13, 1942.

REPORT OF THE RUMFORD COMMITTEE

A meeting of the Rumford Committee was held October 6, 1941. At that meeting the following grants were made:

No. 366	To Professor C. T. Elvey for the construction and use of apparatus for studying the light of the night sky	$400
No. 367	To Dr. K. W. Meissner to assist in the construction of his atomic beam apparatus.	250
No. 368	To Dr. E. J. Schremp in continued support of his cosmic ray researches.	400
No. 369	To Dr. G. Z. Dimitroff to aid in his studies of the sensitivity of photographic emulsions.	400

Grants made by correspondence between December 10, 1941 and April 13, 1942 were as follows:

October 16, 1941		
No. 370	To Professor Wilson M. Powell in continued support of cosmic ray researches.	$250
April 13, 1942		
No. 371	To Professors J. C. Stearns and D. K. Froman to aid in their study of mesotrons in the cosmic rays at both Denver and Mount Evans.	400

Letters were sent to sixteen recipients of grants made between October 2, 1939, and October 6, 1941. In their replies eight grantees reported progress in their investigations while five stated that the war was interfering with their researches. From the three remaining no replies were received.

On October 8, 1941, the Rumford Medals were presented by the Academy to Dr. Vladimir Kosma Zworykin for his "Invention of the Iconoscope and Other Television Devices."

Following the award of these medals Dr. Zworykin addressed the Academy, the subject of his address being "The Electron Microscope."

Respectfully submitted,
NORTON ADAMS KENT,
Chairman

May 13, 1942.

REPORT OF THE C. M. WARREN COMMITTEE

The Committee had at its disposal during the fiscal year, 1941–42, the sum of $1,000. From this amount a total of $975 has been granted as follows:

To Professor H. S. Booth of Western Reserve University, Cleveland, Ohio, a grant of $300, awarded with the agreement that Western Reserve University contribute the balance of $220 needed for the purchase of a Mueller bridge for use in investigations on the physical constants of gases.

To Professor G. Krotkov of Queen's University, Kingston, Ontario, the amount of $180 for the purchase of a photoelectric colorimeter for his work on investigations of the biochemical changes in apples during storage.

To Professor J. W. McBain of Stanford University, California, the sum of $395 for the purchase of a lumetron photoelectric colorimeter with mercury vapor lamp and quartz optical system, cell, and selected filters. This apparatus is for use in investigating the problem of solubilization of substances.

To Dr. Philip Pizzolato of Louisiana State University, New Orleans, Louisiana, a grant of $100 for the purchase of materials (animals, stains, and chemicals) for investigations pertaining to the effect of amino acids, purins, hormones, and vitamins on the creatine-creatinine relationships in muscle metabolism.

The balance of $25 not awarded will be added to the principal.

A report on work accomplished has been received from Professor Krotkov, and reprints covering work assisted by grants have been received from:

Professor E. C. Gilbert: "The Heat of Combustion of cis- and trans-Decahydro-naphthalene." G. F. Davies and E. C. Gilbert, J. Am. Chem. Soc. *63*, 1585 (1941).

Professor Paul L. Kirk: "Microscopy of the Amino Acids and Their Compounds." K. Inouye, R. Sunderlein and P. L. Kirk. Ind. and Eng. Chem. *13*, 587 (1941).

Professor G. Krotkov: "The Respiratory Metabolism of McIntosh Apples, During Ontogeny, as Determined at 22° C." Plant Physiology, *16*, p. 799 (1941).

Apparatus purchased through a grant from the fund has been returned to the Chairman by Professor J. L. Jones of Howard University, Washington, D. C. This apparatus consists of: 2 greaseless high vacuum glass valves; 1 Weston photronic cell No. 2a; 1 housing for photronic cell; 1 set of numbered glass filters (Corning); 2 Bausch and Lomb lenses (numbered); 1 book gold foil; 1 piece platinum wire; 1 electric furnace—consisting of No. 18 nichrome wire wrapped on an aluminum cylinder covered with asbestos. The furnace will maintain a temperature of 400° C. indefinitely and has two sets of heating windings. The furnace is equipped with pyrex windows for visual observation of vessels placed in the aluminum shield.

Respectfully submitted,
FREDERICK G. KEYES,
Chairman

May 13, 1942.

REPORT OF THE COMMITTEE OF PUBLICATION

The Publication Committee has held one meeting during the year, other necessary business having been transacted by correspondence. Six numbers of the *Proceedings* (Vol. 74, Nos. 8–13) were published in the course of the year and also one number of the *Memoirs* (Vol. 19, No. 1).

In connection with Professor and Mrs. Kirsopp Lake's *Dated Greek Manuscripts*, the Chairman has to report that the Index to the ten fascicules already published is nearing completion. Work on this has been somewhat delayed owing to the impending removal of Mr. and Mrs. Lake to Southern California. They expect, however, to send the manuscript in before they depart in September. Work on Professor Hatch's *Album of Dated Syriac Manuscripts* is progressing rapidly. The plates were completed and printed last spring by the Meriden Gravure Company, but the Editor was unwilling to proceed further until the funds necessary for the letterpress were assured. This has become possible through the action of the Council by making available $1,000 from the Amory Fund, which will be repaid by appropriations from the Publication Fund and the proceeds of the book. The printing of the letterpress has been entrusted to the J. H. Furst Company of Baltimore, and three-quarters of the galley proof has been received and corrected. It is anticipated that the book will appear in the fall, as the Index will have to be compiled from the page proof.

$100 from the Publication Funds were contributed towards a volume of Studies in the History of Culture offered to Mr. Waldo G. Leland of the ACLS. The Editor contributed a paper to it on behalf of the Academy.

The Rumford Committee has been of material assistance to our Committee by making appropriations toward publication in the *Proceedings* of studies by Professor Beattie and Associates (Vol. 74, 11) and of two papers by Professor Bridgman (Vol. 74, 12 and 13).

The funds that we shall have available after meeting our outstanding obligations will permit only a small amount of publication for the ensuing year, nor is there, it would appear, much hope of obtaining additional assistance for printing the papers next in line.

The Chairman has one general suggestion to offer, namely, that the main bulk of the unsold numbers of Professor and Mrs. Lake's *Dated Greek Manuscripts* be sent on from Baltimore to Boston and stored in the Academy's House. He is apprised that room is available there. A small number of copies of each fascicule could be left with the Waverly Press to meet current orders, and these could be replenished from time to time from the stock held in Boston. Such an arrangement would save us a considerable sum in storage charges which would otherwise eat into the balance of the subsidy from the Carnegie Corporation which we are holding in trust against an eventual eleventh and final fascicule of the series.

May 1, 1941

General Publication Fund:	
Receipts: Overdraft	$215.91
Appropriation	2,350.00
Expenditures	1,732.44
Balance	$591.70
Hatch Fund:	
Balance	$1,452.82
Rec. ACLS	1,168.00
Expenditures	2,162.20
Balance	$459.82
Lake Fund:	
Balance	$709.28
Rec. Christophers	149.75
Expenditures	172.00
Balance	$682.03

Respectfully submitted,
ROBERT P. BLAKE,
Chairman

May 13, 1942.

REPORT OF THE HOUSE COMMITTEE

During the year ending March 31, 1942, the House Committee has had at its disposal funds amounting to $2,170, made up as follows:

Appropriation for 1941–1942	$2,000
Received from other societies for the use of rooms	170
Total	$2,170

The expenditures amounted to $2,395.81. Of this the sum of $2,162.28 was spent for the routine expenses, janitor, heat, light, telephone, etc. and $233.53 for upkeep, furnishings and equipment, including blackout shades and other equipment needed in the event of air raids.

Meetings have been held as follows:

The Academy: Stated meetings	8
Group discussion meetings	3
American Oriental Society	1
Boston Surgical Society	3
Committee on Russian War Relief	1
Friends of China, Inc.	4
Geological Society of Boston	1
Mediaeval Academy of America	1
New England Botanical Club	9
Pan American Society of Massachusetts	4
Solar Conference	1
Trustees of the Sharon Sanatorium	1
Total	37

The Council Chamber has been used for Academy Council and Committee meetings, and also by the Trustees of the Children's Museum and the New England Farm and Garden Association.

A detailed list of expenditures follows:

Janitor	$963.00
Electricity: Light	196.17
Power	73.58
Fuel	595.60
Elevator service and repairs	99.26
Telephone	114.16
Gas	50.40
Water	40.48
Upkeep	107.90
Furnishings and equipment	125.63
Janitor's supplies and sundries	29.63
Total	$2,395.81

Respectfully submitted,
E. F. LANGLEY,
Chairman

May 13, 1942.

On the recommendation of the Treasurer, the Academy voted that the annual assessment for the year 1942–1943 for resident Fellows be ten dollars.

The annual election of officers and committees resulted as follows:

Harlow Shapley, *President*
Percy W. Bridgman, *Vice-President for Class I*
S. Burt Wolbach, *Vice-President for Class II*
Sidney B. Fay, *Vice-President for Class III*
Fred N. Robinson, *Vice-President for Class IV*
Abbott P. Usher, *Corresponding Secretary*
Hudson Hoagland, *Recording Secretary*
Horace S. Ford, *Treasurer*
Frederick H. Pratt, *Librarian*
Robert P. Blake, *Editor*

Councillors for Four Years:

Bart J. Bok, of Class I
Louis C. Graton, of Class II
Edward S. Thurston, of Class III
Edgar S. Brightman, of Class IV

Committee on Policy and Resources:

Member for Five Years and Chairman:

Henry S. Dennison

Member for Two Years:

Horace S. Ford

Finance Committee:

Jerome C. Hunsaker
Ralph E. Freeman
Henry P. Kendall
John F. Ebersole

Rumford Committee:

Norton A. Kent, *Chairman*
Percy W. Bridgman
Harry M. Goodwin
Harlow Shapley
George W. Pierce
George R. Harrison
Robert B. Lindsay

C. M. Warren Committee:

Frederick G. Keyes *Chairman*
Gregory P. Baxter
Walter L. Jennings
Tenney L. Davis
Charles A. Kraus
Reid Hunt
Grinnell Jones

Committee of Publication

Robert P. Blake, *Chairman*
Edwin C. Kemble, of Class I
Ralph H. Wetmore, of Class II
Joseph H. Beale, of Class III
Robert P. Casey, of Class IV

Committee on the Library:

Frederick H. Pratt, *Chairman*
Raymond C. Archibald, of Class I
Thomas Barbour, of Class II
Francis N. Balch, of Class III
Henry B. Washburn, of Class IV

Auditing Committee:

Erwin H. Schell
Alexander Forbes

House Committee:

Ernest F. Langley, *Chairman*
H. Addington Bruce
Robert P. Bigelow
Walter E. Clark

Committee on Biographical Notices:

Hudson Hoagland, *Chairman*

For Three Years:

Alfred C. Lane
Joseph H. Beale

For Two Years:

Hervey W. Shimer

Committee on Meetings:

The President
The Recording Secretary
Leonard Carmichael
Samuel H. Cross
George Scatchard
Frederick K. Morris

The Corresponding Secretary announced that the following had been elected members of the Academy:

FELLOWS

Class I

Section 1. Otto Struve, Williams Bay, Wis.
Section 2. Francis Birch, Cambridge
Section 3. Samuel Cornette Collins, Cambridge
Section 4. Wilmer Lanier Barrow, Concord

Class II

Section 1. Russell Gibson, Belmont
Section 2. William Ralph Maxon, Washington, D. C.
Section 3. Hermann Joseph Muller, Amherst
Section 4. William Irving Clark, Worcester
Samuel Albert Levine, Newton Centre

Class III

Section 3. Howard Sylvester Ellis, Berkeley, Cal.
Wassily W. Leontief, Cambridge

William Andrew Paton, Ann Arbor, Mich.
Paul Anthony Samuelson, Cambridge
Section 4. Donald Kirk David, Winchester
Daniel L. Marsh, Boston
Roger Sherman Greene, Worcester

CLASS IV

Section 1. Richard Peter McKeon, Chicago, Ill.
Section 2. Henry Joel Cadbury, Cambridge
Section 4. John Nash Douglas Bush, Cambridge
Otto Kinkeldey, Ithaca, N. Y.
Carl Sandburg, Harbert, Mich.

FOREIGN HONORARY MEMBER

CLASS II

Section 2. Lorenzo R. Parodi, Buenos Aires, Argentina

The following communication was then presented:

Mark Graubard: "Morale for a Democratic Offensive."

An exhibit of specimens of extinct birds, loaned by the New England Museum of Natural History, was described by Mr. C. Russell Mason.

The meeting was dissolved at 10.30 P. M.

PRESIDENTS OF THE ACADEMY

1780–1791	James Bowdoin
1791–1814	John Adams
1814–1820	Edward Augustus Holyoke
1820–1829	John Quincy Adams
1829–1838	Nathaniel Bowditch
1838–1839	James Jackson
1839–1846	John Pickering
1846–1863	Jacob Bigelow
1863–1873	Asa Gray
1873–1880	Charles Francis Adams
1880–1892	Joseph Lovering
1892–1894	Josiah Parsons Cooke
1894–1903	Alexander Agassiz
1903–1908	William Watson Goodwin
1908–1915	John Trowbridge
1915–1917	Henry Pickering Walcott
1917–1919	Charles Pickering Bowditch
1919–1921	Theodore William Richards
1921–1924	George Foot Moore
1924–1927	Theodore Lyman
1927–1931	Edwin Bidwell Wilson
1931–1933	Jeremiah Denis Matthias Ford
1933–1935	George Howard Parker
1935–1937	Roscoe Pound
1937–1939	Dugald Caleb Jackson
1939–	Harlow Shapley

American Academy of Arts and Sciences.

OFFICERS AND COMMITTEES FOR 1942–1943.

PRESIDENT.

Harlow Shapley.

VICE-PRESIDENTS.

Class I.	Class II.	Class III.	Class IV.
Percy W. Bridgman,	S. Burt Wolbach,	Sidney B. Fay,	Fred N. Robinson.

CORRESPONDING SECRETARY.

Abbott P. Usher.

RECORDING SECRETARY.

Hudson Hoagland.

TREASURER.

Horace S. Ford.

LIBRARIAN.

Frederick H. Pratt.

EDITOR.

Robert P. Blake.

COUNCILLORS.

Class I.		Class II.
Edward L. Moreland,	*Terms expire* 1943.	Ivan M. Johnston.
Arthur A. Blanchard,	*Terms expire* 1944.	William B. Castle.
Norton A. Kent,	*Terms expire* 1945.	David Rapport.
Bart J. Bok,	*Terms expire* 1946.	Louis J. Graton.

Class III.		Class IV.
Arthur N. Holcombe,	*Terms expire* 1943.	S. Foster Damon.
Henry P. Kendall,	*Terms expire* 1944.	Charles H. Taylor.
Edward H. Chamberlin,	*Terms expire* 1945.	Samuel H. Cross.
Edward S. Thurston,	*Terms expire* 1946.	Edgar S. Brightman.

COMMITTEE OF FINANCE.

Jerome C. Hunsaker, Ralph E. Freeman, Henry P. Kendall, John F. Ebersole

COMMITTEE ON POLICY AND RESOURCES

Henry S. Dennison, *Chairman*,
The President, *ex officio*,
Horace S. Ford, Robert G. Dodge, Dugald C. Jackson, W. Cameron Forbes.

RUMFORD COMMITTEE.

Norton A. Kent, *Chairman*,
Percy W. Bridgman, Harlow Shapley, George R. Harrison,
Harry M. Goodwin, George W. Pierce, Robert B. Lindsay.

C. M. WARREN COMMITTEE.

Frederick G. Keyes, *Chairman*,
Gregory P. Baxter,
Reid Hunt,
Tenney L. Davis,
Walter L. Jennings,
Charles A. Kraus,
Grinnell Jones.

COMMITTEE OF PUBLICATION

Robert P. Blake, *Chairman*,
Edwin C. Kemble, of Class I,
Joseph H. Beale, of Class III,
Ralph H. Wetmore, of Class II,
Robert P. Casey, of Class IV.

COMMITTEE ON THE LIBRARY.

Frederick H. Pratt, *Chairman*,
Raymond C. Archibald, of Class I,
Francis N. Balch, of Class III,
Thomas Barbour, of Class II,
Henry B. Washburn, of Class IV.

AUDITING COMMITTEE.

Erwin H. Schell,
Alexander Forbes

HOUSE COMMITTEE.

Ernest F. Langley, *Chairman*,
Robert P. Biglow,
Walter E. Clark,
H. Addington Bruce.

COMMITTEE ON BIOGRAPHICAL NOTICES.

Hudson Hoagland, *Chairman*,
Raymond C. Archibald,
Joseph H. Beale,
Samuel E. Morison,
Alfred C. Lane,
Hervey W. Shimer.

COMMITTEE ON MEETINGS

The President,
The Recording Secretary,
Leonard Carmichael,
George Scatchard,
Frederick K. Morris,
Samuel H. Cross.

LIST

OF THE

FELLOWS AND FOREIGN HONORARY MEMBERS

(Corrected to September 1, 1942)

FELLOWS—796

(Number limited to eight hundred)

The year of election is indicated in the left margin, the century being omitted; thus 21 means 1921, 92 means 1892. When a Fellow resigned and was re-elected, the year of re-election is indicated in the ordinary way, the year of election is enclosed in square brackets. The year of election of an Associate, now a Fellow, is indicated by round brackets.

CLASS I—Mathematical and Physical Sciences—213

Section I—*Mathematics and Astronomy*—48

21	Charles Greeley Abbot	Washington, D. C.
32	Clarence Raymond Adams	Providence, R. I.
22	Walter Sydney Adams	Pasadena, Cal.
12	George Russell Agassiz	Boston
17	Raymond Clare Archibald	Providence, R. I.
32	Albert Arnold Bennett	Providence, R. I.
13	George David Birkhoff	Cambridge
35	Gilbert Ames Bliss	Chicago, Ill.
39	Bart Jan Bok	Lexington
13	Julian Lowell Coolidge	Cambridge
15	Leonard Eugene Dickson	Chicago, Ill.
33	Jesse Douglas	Brooklyn, N. Y.
38	John Charles Duncan	Wellesley
34	Griffith Conrad Evans	Berkeley, Cal.
15	Philip Fox	Evanston, Ill.
30	Philip Franklin	Belmont
32	Einar Hille	New Haven, Conn.
15	Frank Lauren Hitchcock	Belmont
13	Edward Vermilye Huntington	Cambridge
15	Dunham Jackson	Minneapolis, Minn.
38	E[lvin] Morton Jellinek	New York, N. Y.
15	Carl Otto Lampland	Flagstaff, Ariz.
25	Willem Jacob Luyten	Minneapolis, Minn.
34	Donald Howard Menzel	Cambridge
19	George Abram Miller	Urbana, Ill.
24	John Anthony Miller	Wallingford, Pa.
23	Samuel Alfred Mitchell	University, Va.
29	Marston Morse	Princeton, N. J.
19	Forest Ray Moulton	Washington, D. C.
18	Henry Bayard Phillips	Belmont
96	Charles Lane Poor	New York, N. Y.
14	Roland George Dwight Richardson	Providence, R. I.
21	Henry Norris Russell	Princeton, N. J.
21	Frank Schlesinger	New Haven, Conn.
20	Harlow Shapley	Cambridge
09	Vesto Melvin Slipher	Flagstaff, Ariz.
17	Frederick Slocum	Middletown, Conn.
19	Virgil Snyder	Ithaca, N. Y.
21	Joel Stebbins	Madison, Wis.
27	Harlan True Stetson	Needham
30	Dirk Jan Struik	Belmont
42	Otto Struve	Williams Bay, Wis.
28	Jacob David Tamarkin	Providence, R. I.
23	Oswald Veblen	Princeton, N. J.
29	Joseph Leonard Walsh	Cambridge
41	Fred Lawrence Whipple	Cambridge
25	Alfred North Whitehead	Cambridge
32	David Vernon Widder	Cambridge

Class I, Section II—*Physics*—60

28	Adelbert Ames, Jr.	Hanover, N. H.
11	Joseph Sweetman Ames	Baltimore, Md.
37	Kenneth Tompkins Bainbridge	Cambridge
21	Samuel Jackson Barnett	Los Angeles, Cal.
42	Francis Birch	Cambridge
12	Percy Williams Bridgman	Cambridge
39	Lyman James Briggs	Washington, D. C.
26	Walter Guyton Cady	Middletown, Conn.
03	George Ashley Campbell	Upper Montclair, N. J.
21	Leslie Lyle Campbell	Lexington, Va.
16	Emory Leon Chaffee	Belmont
28	Arthur Holly Compton	Chicago, Ill.
31	Karl Taylor Compton	Cambridge
12	Daniel Frost Comstock	Lincoln
15	William David Coolidge	Schenectady, N. Y.
34	Franzo Hazlett Crawford	Williamstown
13	Henry Crew	Evanston, Ill.
11	Harvey Nathaniel Davis	Hoboken, N. J.
29	Clinton Joseph Davisson	New York, N. Y.
12	Arthur Louis Day	Bethesda, Md.
14	William Johnson Drisko	Addison, Me.

01 Alexander Wilmer Duff..............Worcester
09 Arthur Woolsey Ewell................Worcester
39 Harry Edward Farnsworth.......Providence, R. I.
97 Harry Manley Goodwin..............Brookline
29 Arthur Cobb Hardy..................Wellesley
31 George Russell Harrison................Belmont
95 Hammond Vinton Hayes...............Boston
14 John Charles Hubbard..........Baltimore, Md.
17 Gordon Ferrie Hull.............Hanover, N. H.
40 Frederick Vinton Hunt.................Belmont
14 James Edmund Ives.........Washington, D. C.
22 Edwin Crawford Kemble............Cambridge
13 Norton Adams Kent............Newton Center
37 Ernest Orlando Lawrence..........Berkeley, Cal.
99 Henry Lefavour.......................Boston
31 Robert Bruce Lindsay..........Providence, R. I.
01 Theodore Lyman....................Brookline
34 Louis Williams McKeehan....New Haven, Conn.
14 Ernest George Merritt..............Ithaca, N. Y.
14 Robert Andrews Millikan.........Pasadena, Cal.
34 Harry Rowe Mimno............East Lexington
34 Philip McCord Morse.................Belmont
31 Otto Oldenberg.....................Cambridge
34 Leigh Page...................New Haven, Conn.
07 George Washington Pierce...........Cambridge
41 Isidor Isaac Rabi..............New York, N. Y.
27 John Clarke Slater...................Cambridge
37 George William Stewart...........Iowa City, Ia.
96 John Stone Stone...............San Diego, Cal.
37 Jabez Curry Street..................Cambridge
12 Maurice deKay Thompson............Brookline
28 Manuel Sandoval Vallarta............Brookline
35 Robert Jemison Van de Graaff..........Belmont
34 John Hasbrouck Van Vleck...........Cambridge
35 Bertram Eugene Warren.............Cambridge
18 David Locke Webster............Palo Alto, Cal.
11 Edwin Bidwell Wilson.................Brookline
13 Robert Williams Wood..........Baltimore, Md.
17 John Zeleny.................New Haven, Conn.

CLASS I, SECTION III—*Chemistry*—56

26 Roger Adams.......................Urbana, Ill.
13 Wilder Dwight Bancroft...........Ithaca, N. Y.
07 Gregory Paul Baxter................Cambridge
29 James Alexander Beattie...............Belmont
19 Arthur Alphonzo Blanchard............Brookline
14 Marston Taylor Bogert.........New York, N. Y.
36 Harold Simmons Booth............Cleveland, O.
11 William Crowell Bray.............Berkeley, Cal.
38 Emile Monnin Chamot.............Ithaca, N. Y.
12 Russell Henry Chittenden......New Haven, Conn.
41 George Whiteley Coggeshall..........Cambridge
42 Samuel Cornette Collins.............Cambridge
24 James Bryant Conant................Cambridge
23 Tenney Lombard Davis.................Norwell
37 John Tileston Edsall...................Dedham
37 Gustavus John Esselen..............Swampscott
40 William Lloyd Evans.............Columbus, O.
33 Louis Frederick Fieser..................Belmont
15 George Shannon Forbes..............Cambridge
35 Louis Harris.........................Cambridge
36 Albert Baird Hastings................Cambridge
38 Robert Casad Hockett..................Concord
36 Ernest Hamlin Huntress.......Melrose Highlands
97 Walter Louis Jennings...............Cambridge
18 Grinnell Jones.......................Cambridge
19 Frederick George Keyes.............Cambridge
33 George Bogdan Kistiakowsky.........Cambridge
15 Charles August Kraus...........Providence, R. I.
14 Arthur Becket Lamb..................Brookline
18 Irving Langmuir............Schenectady, N. Y.
09 Gilbert Newton Lewis.............Berkeley, Cal.
15 Warren Kendall Lewis..................Newton
23 Duncan Arthur MacInnes......New York, N. Y.
32 Kenneth Lamartine Mark................Boston
41 Charles Edward Kenneth Mees...Rochester, N. Y.
35 Nicholas Athanasius Milas..............Belmont
36 Avery Adrian Morton...............Watertown
19 Edward Mueller.....................Cambridge
31 William Albert Noyes, Jr.........Rochester, N. Y.
14 Samuel Cate Prescott................Brookline
39 Clifford Burrough Purves............Cambridge
79 Robert Hallowell Richards.........Jamaica Plain
14 Martin André Rosanoff...........Pittsburgh, Pa.
28 George Scatchard....................Cambridge
32 Walter Cecil Schumb...............East Milton
15 Miles Standish Sherrill................Brookline
20 Harry Monmouth Smith..............Brookline
34 Leighton Bruerton Smith................Beverly
22 Richard Chace Tolman............Pasadena, Cal.
38 Harold Clayton Urey..............Leonia, N. J.
41 Harry Boyer Weiser..............Houston, Tex.
39 Frank Clifford Whitmore......State College, Pa.
11 Willis Rodney Whitney........Schnectady, N. Y.
19 Robert Seaton Williams................Belmont
34 David Elbridge Worrall................Medford
41 Ralph Chillingworth Young............Arlington

CLASS I, SECTION IV—*Technology and Engineering*—49

06 Comfort Avery Adams..........Philadelphia, Pa.
33 Harold Kilbrith Barrows............Winchester
31 Charles Harold Berry..................Belmont
41 Edward Lindley Bowles...............Wellesley
25 Vannevar Bush..............Washington, D. C.
34 Otto Gustav Colbiornsen Dahl..........Brookline
34 Chester Laurens Dawes...............Cambridge
38 Alfred Victor de Forest...............Cambridge
34 Jacob Pieter Den Hartog..........Wellesley Hills
20 Theodore Harwood Dillon.....Washington, D. C.
41 Charles Stark Draper...................Newton
22 Gano Dunn.....................New York, N. Y.
21 William Frederick Durand........Palo Alto, Cal.
27 Gordon Maskew Fair................Cambridge
19 Frederic Harold Fay....................Boston
32 Glennon Gilboy.........................Lincoln
32 Albert Haertlein....................Watertown
40 Harold Locke Hazen..................Belmont
36 Murray Philip Horwood..........Newton Center

23	William Hovgaard	Brooklyn, N. Y.
34	Jerome Clarke Hunsaker	Boston
23	James Robertson Jack	Watertown
11	Dugald Caleb Jackson	Cambridge
30	Frank Baldwin Jewett	New York, N. Y.
01	Lewis Jerome Johnson	Cambridge
37	Joseph Henry Keenan	Belmont
32	Ralph Restieaux Lawrence	Belmont
23	William Henry Lawrence	Jamaica Plain
38	John Moyes Lessells	Brookline
21	Charles Thomas Main	Winchester
12	Lionel Simeon Marks	Cambridge
34	Edward Leyburn Moreland	Wellesley
20	Frederick Law Olmsted	Elkton, Md.
15	Charles Francis Park	Taunton
28	Langdon Pearse	Chicago, Ill.
13	Harold Pender	Philadelphia, Pa.
30	Greenleaf Whittier Pickard	Newton Center
41	Reinhold Rüdenberg	Belmont
30	George Edmond Russell	Bedford
01	Henry Lloyd Smyth	Windsor, Vt.
39	C. Richard Soderberg	Weston
14	Charles Milton Spofford	Boston
28	John F. Stevens	Baltimore, Md.
23	Edward Pearson Warner	New York, N. Y.
37	Harald Malcolm Westergaard	Belmont
27	Robert Spurr Weston	Brookline
15	Joseph Ruggles Worcester	Waltham
40	John Wulff	Cambridge
41	Vladimir Kosma Zworykin	Camden, N. J.

CLASS II—NATURAL AND PHYSIOLOGICAL SCIENCES—211

SECTION I—*Geology, Mineralogy, and Physics of the Globe*—50

15	Wallace Walter Atwood	Worcester
41	Alan Mara Bateman	New Haven, Conn.
38	Marland Pratt Billings	Wellesley
21	Norman Levi Bowen	Chicago, Ill.
16	Isaiah Bowman	Baltimore, Md.
33	Charles Franklin Brooks	Milton
29	Kirk Bryan	Cambridge
33	Frank Morton Carpenter	Lexington
93	Henry Helm Clayton	Canton
09	Reginald Aldworth Daly	Cambridge
34	Sterling Price Fergusson	Milton
42	Russell Gibson	Belmont
17	James Walter Goldthwait	Hanover, N. H.
14	Louis Caryl Graton	Cambridge
17	Herbert Ernest Gregory	Honolulu, T. H.
21	William Jackson Humphreys	Washington, D. C.
16	Ellsworth Huntington	New Haven, Conn.
95	Robert Tracy Jackson	Peterborough, N. H.
02	Thomas Augustus Jaggar	Honolulu, T. H.
08	Douglas Wilson Johnson	New York, N. Y.
21	Arthur Keith	Washington, D. C.
10	Alfred Church Lane	Cambridge
25	Esper Signius Larsen, Jr.	Belmont
15	Andrew Cowper Lawson	Berkeley, Cal.
16	Charles Kenneth Leith	Madison, Wis.
17	Alexander George McAdie	Hampton, Va.
31	George Francis McEwen	La Jolla, Cal.
27	Donald Hamilton McLaughlin	Berkeley, Cal.
25	Kirtley Fletcher Mather	Newton Center
26	Edward Bennett Mathews	Baltimore, Md.
35	Warren Judson Mead	Cambridge
21	John Campbell Merriam	Washington, D. C.
17	William John Miller	Los Angeles, Cal.
32	Frederick Kuhne Morris	Cambridge
34	Walter Harry Newhouse	Medford
17	Percy Edward Raymond	Lexington
22	Austin Flint Rogers	Palo Alto, Cal.
34	Carl-Gustaf Arvid Rossby	Washington, D. C.
15	Robert Wilcox Sayles	Chestnut Hill
19	Waldemar Theodore Schaller	Washington, D. C.
15	Charles Schuchert	New Haven, Conn.
12	William Berryman Scott	Princeton, N. J.
11	Hervey Woodburn Shimer	Hingham
41	Chester Stock	Pasadena, Cal.
17	Thomas Wayland Vaughan	Washington, D. C.
08	Charles Hyde Warren	New Haven, Conn.
14	Herbert Percy Whitlock	New York, N. Y.
35	Derwent Stainthorpe Whittlesey	Cambridge
15	Bailey Willis	Palo Alto, Cal.
15	Frederick Eugene Wright	Washington, D. C.

CLASS II, SECTION II—*Botany*—37

30	LeRoy Abrams	Stanford University, Cal
11	Oakes Ames	North Easton
34	Edgar Anderson	St. Louis, Mo.
15	Irving Widmer Bailey	Cambridge
00	Liberty Hyde Bailey	Ithaca, N. Y.
21	Edward Wilber Berry	Baltimore, Md.
40	Albert Francis Blakeslee	Cold Spring Harbor, N. Y.
98	Douglas Houghton Campbell	Palo Alto, Cal.
16	Bradley Moore Davis	Ann Arbor, Mich.
35	Bernard Ogilvie Dodge	New York, N. Y.
41	Arthur Johnson Eames	Ithaca, N. Y.
21	Rollins Adams Emerson	Ithaca, N. Y.
12	Alexander William Evans	New Haven, Conn.
29	Joseph Horace Faull	Cambridge
00	Merritt Lyndon Fernald	Cambridge
11	Robert Almer Harper	New York, N. Y.
98	John George Jack	East Walpole
28	Willis Linn Jepson	Berkeley, Cal.
27	Ivan Murray Johnston	Brookline
34	Donald Forsha Jones	New Haven, Conn.
14	Burton Edward Livingston	Riderwood, Md.
40	Paul Christoph Mangelsdorf	Cambridge
42	William Ralph Maxon	Washington, D. C.
21	Elmer Drew Merrill	Jamaica Plain
10	Winthrop John Vanleuven Osterhout	New York, N. Y.
27	George James Peirce	Palo Alto, Cal.
14	Alfred Rehder	Jamaica Plain
30	Karl Sax	Jamaica Plain
16	William Albert Setchell	Berkeley, Cal.

34	Edmund Ware Sinnott	New Haven Conn.
34	Gilbert Morgan Smith	Stanford University, Cal.
23	Elvin Charles Stakman	St. Paul, Minn.
38	Kenneth Vivian Thimann	Cambridge
92	William Trelease	Urbana, Ill.
31	Charles Alfred Weatherby	Cambridge
22	William Henry Weston, Jr.	Cambridge
32	Ralph Hartley Wetmore	Belmont

CLASS II, SECTION III—*Zoology and Physiology*—67

22	Nathan Banks	Jamaica Plain
16	Thomas Barbour	Boston
33	Philip Bard	Baltimore, Md.
09	Francis Gano Benedict	Machiasport, Me.
11	Henry Bryant Bigelow	Concord
14	Robert Payne Bigelow	Brookline
35	Charles Henry Blake	Lincoln
20	William T. Bovie	Waterville, Me.
24	Edward Allen Boyden	Minneapolis, Minn.
16	John Lewis Bremer	Boston
15	Charles Thomas Brues	Newtonville
28	John Wymond Miller Bunker	Belmont
06	Walter Bradford Cannon	Cambridge
22	Thorne Martin Carpenter	Boston
00	William Ernest Castle	Berkeley, Cal.
29	Lemuel Roscoe Cleveland	Jamaica Plain
26	Edwin Joseph Cohn	Cambridge
14	Edwin Grant Conklin	Princeton, N. J.
23	Manton Copeland	Brunswick, Me.
27	William John Crozier	Cambridge
17	Joseph Augustine Cushman	Sharon
35	J[ohn] Frank[lin] Daniel	Berkeley, Cal.
95	Charles Benedict Davenport	Cold Spring Harbor
29	Hallowell Davis	Belmont
33	Alden Benjamin Dawson	Belmont
25	Samuel Randall Detwiler	New York, N. Y.
25	Herbert McLean Evans	Berkeley, Cal.
34	Cyrus Hartwell Fiske	Belmont
15	Alexander Forbes	Milton
34	John Farquhar Fulton	New Haven, Conn.
31	William King Gregory	New York, N. Y.
36	Frederick Lee Hisaw	Cambridge
29	Leigh Hoadley	Cambridge
34	Hudson Hoagland	Worcester
24	Samuel Jackson Holmes	Berkeley, Cal.
28	Roy Graham Hoskins	Waban
13	Leland Ossian Howard	Washington, D. C.
14	Herbert Spencer Jennings	Baltimore, Md.
13	Charles Atwood Kofoid	Berkeley, Cal.
16	Frederic Thomas Lewis	Waban
33	Frank Rattray Lillie	Chicago, Ill.
14	Ralph Stayner Lillie	Chicago, Ill.
17	Richard Swann Lull	New Haven, Conn.
84	Edward Laurens Mark	Cambridge
15	Albert Davis Mead	Providence, R. I.
27	Axel Leonard Melander	New York, N. Y.
35	Karl Friedrich Meyer	San Francisco, Cal.
21	Gerrit Smith Miller	Washington, D. C.
28	Thomas Hunt Morgan	Pasadena, Cal.
42	Hermann Joseph Muller	Amherst
95	George Howard Parker	Cambridge
21	Henry Augustus Pilsbry	Philadelphia, Pa.
39	Gregory Pincus	Worcester
27	Frederick Haven Pratt	Wellesley Hills
09	Herbert Wilbur Rand	Belmont
32	David Rapport	Cambridge
23	Alfred Clarence Redfield	Milton
34	Alfred Newton Richards	Philadelphia, Pa.
34	Oscar Riddle	Cold Spring Harbor, N. Y.
13	William Emerson Ritter	Berkeley, Cal.
37	Alfred Sherwood Romer	Cambridge
39	Arturo Rosenblueth	Watertown
25	Alexander Grant Ruthven	Ann Arbor, Mich.
41	Francis Otto Schmitt	Belmont
15	Arthur Wisswald Weysse	Boston
38	George Bernays Wislocki	Milton
33	Jeffries Wyman, Jr.	Chestnut Hill

CLASS II, SECTION IV—*Medicine and Surgery*—57

41	Fuller Albright	Brookline
32	Joseph Charles Aub	Belmont
36	Oswald Theodore Avery	New York, N. Y.
29	James Bourne Ayer	Milton
(28) 32	Franklin Greene Balch	Boston
41	Walter Bauer	Waban
31	George Blumer	New Haven, Conn.
36	Charles Sidney Burwell	Brookline
21	Charles Macfie Campbell	Cambridge
19	Alexis Carrel	New York, N. Y.
31	William Bosworth Castle	Brookline
30	David Cheever	Boston
13	Henry Asbury Christian	Brookline
42	William Irving Clark	Worcester
21	Rufus Cole	Mount Kisco, N. Y.
32	Elliott Carr Cutler	Brookline
31	Eugene Floyd DuBois	New York, N. Y.
33	Reginald Fitz	Brookline
11	Simon Flexner	New York, N. Y.
27	James Lawder Gamble	Brookline
22	Joseph Lincoln Goodale	Ipswich
21	Ross Granville Harrison	New Haven, Conn.
27	Percy Rogers Howe	Belmont
21	William Henry Howell	Baltimore, Md.
33	Edgar Erskine Hume	Carlisle, Pa.
15	Reid Hunt	Boston
34	Henry Jackson, Jr.	Chestnut Hill
12	Elliott Proctor Joslin	Boston
23	Roger Irving Lee	Brookline
42	Samuel Albert Levine	Newton Center
29	Edwin Allen Locke	Williamstown
28	Warfield Theobald Longcope	Baltimore, Md.
32	Fred Bates Lund	Newton
40	William de Berniere MacNider	Chapel Hill, N. C.
34	Leroy Matthew Simpson Miner	Newtonville
26	George Richards Minot	Brookline
41	Alan Richards Moritz	Waban
28	William Lorenzo Moss	Athens, Ga.
28	John Howard Mueller	West Roxbury

25	Robert Bayley Osgood	Boston
37	Walter Walker Palmer	New York, N. Y.
27	Joseph Hershey Pratt	Boston
35	Tracy Jackson Putnam	New York, N. Y.
34	William Carter Quinby	Brookline
34	Arthur Hiler Ruggles	Providence, R. I.
39	Frederick Fuller Russell	Brookline
39	William Thomas Salter	New Haven, Conn.
27	Andrew Watson Sellards	Boston
33	George Cheever Shattuck	Brookline
30	Torald Hermann Sollmann	Cleveland, O.
14	Richard Pearson Strong	Boston
30	Fritz Bradley Talbot	Brookline
14	Ernest Edward Tyzzer	Wakefield
14	Frederick Herman Verhoeff	Brookline
27	Joseph Treloar Wearn	Cleveland, Ohio
40	Paul Dudley White	Brookline
12	Simeon Burt Wolbach	South Sudbury

CLASS III—The Social Arts—174

Section I—*Jurisprudence*—41

(24) 32	Francis Noyes Balch	Jamaica Plain
38	Henry Moore Bates	Ann Arbor, Mich.
06	Joseph Henry Beale	Cambridge
36	Stoughton Bell	Cambridge
33	Harry Augustus Bigelow	Chicago, Ill.
36	Wilfred Bolster	Wellesley
36	Claude Raymond Branch	Providence, R. I.
33	John Dickinson	Philadelphia, Pa.
38	Robert Gray Dodge	Boston
31	Fred Tarbell Field	Newton
39	Herbert Funk Goodrich	Philadelphia, Pa.
33	Theodore Francis Green	Providence, R. I.
38	Frank Washburn Grinnell	Boston
41	Erwin Nathaniel Griswold	Belmont
39	John Loomer Hall	Boston
39	Augustus Noble Hand	New York, N. Y.
33	Learned Hand	New York, N. Y.
39	Albert James Harno	Urbana, Ill.
18	Charles Evans Hughes	Washington, D. C.
38	Melvin Maynard Johnson	Brookline
38	James McCauley Landis	Cambridge
32	Sayre Macneil	Azusa, Cal.
32	Calvert Magruder	Cambridge
31	William DeWitt Mitchell	New York, N. Y.
31	Edmund Morris Morgan	Arlington
36	Henry Parkman, Jr.	Boston
39	Robert Porter Patterson	Washington, D. C.
01	George Wharton Pepper	Philadelphia, Pa.
11	Roscoe Pound	Watertown
38	William Morton Prest	Boston
36	Stanley Elroy Qua	Lowell
32	Francis Bowes Sayre	Washington, D. C.
21	Austin Wakeman Scott	Cambridge
35	James Brown Scott	Washington, D. C.
36	Sidney Post Simpson	Cambridge
33	Harlan Fiske Stone	Washington, D. C.
39	Thomas Walter Swan	New York, N. Y.
32	Edward Sampson Thurston	Cambridge
38	Bentley Wirt Warren	Boston
37	Joseph Warren	Brookline
(28) 32	Edmund Allen Whitman	Cambridge

Class III, Section II—*Government, International Law, and Diplomacy*—28

36	Howard Landis Bevis	Columbus, O.
33	Edwin Montefiore Borchard	New Haven, Conn.
40	Robert Granville Caldwell	Belmont
32	William Richards Castle, Jr.	Washington, D. C.
32	Joseph Perkins Chamberlain	New York, N. Y.
33	Robert Treat Crane	New York, N. Y.
35	Tyler Dennett	Hague, N. Y.
31	Sidney Bradshaw Fay	Cambridge
27	William Cameron Forbes	Norwood
34	Edgar Stephenson Furniss	New Haven, Conn.
32	Joseph Clark Grew	Hancock, N. H.
35	Charles Grove Haines	Los Angeles, Cal.
16	Albert Bushnell Hart	Cambridge
41	Hajo Holborn	New Haven, Conn.
27	Arthur Norman Holcombe	Cambridge
31	Manley Ottmer Hudson	Cambridge
32	Philip Carryl Jessup	New York, N. Y.
97	Abbott Lawrence Lowell	Boston
32	Charles Edward Merriam	Chicago, Ill.
19	John Bassett Moore	New York, N. Y.
13	William Bennett Munro	Pasadena, Cal.
41	Gaetano Salvemini	Cambridge
40	Thomas Head Thomas	Cambridge
27	Westel Woodbury Willoughby	Washington, D. C.
32	William Franklin Willoughby	Washington, D. C.
14	George Grafton Wilson	Grafton, Vt.
27	Quincy Wright	Chicago, Ill.
33	Henry Aaron Yeomans	Cambridge

Class III, Section III—*Economics and Sociology*—69

36	James Waterhouse Angell	New York, N. Y.
36	James Cummings Bonbright	New York, N. Y.
33	Harold Hitchings Burbank	Cambridge
36	Edward Hastings Chamberlin	Cambridge
34	John Maurice Clark	Westport, Conn.
28	Arthur Harrison Cole	Cambridge
31	Melvin Thomas Copeland	Cambridge
31	William Leonard Crum	Cambridge
32	William James Cunningham	Cambridge
34	Winthrop More Daniels	Saybrook Point, Conn.
21	Clive Day	New Haven, Conn.
13	Davis Rich Dewey	Cambridge
32	Arthur Stone Dewing	Newton
41	Carl Rupp Doering	Cambridge
32	Wallace Brett Donham	Boston
34	John Franklin Ebersole	Belmont
42	Howard Sylvester Ellis	Berkeley, Cal.
36	Fred Rogers Fairchild	New Haven, Conn.
36	Frank Albert Fetter	Princeton, N. J.
12	Irving Fisher	New Haven, Conn.
31	James Ford	Lincoln
34	Ralph Evans Freeman	Cambridge
13	Edwin Francis Gay	Pasadena, Cal.

33	Sheldon Glueck	Cambridge
39	Gottfried Haberler	Cambridge
34	Robert Murray Haig	New York, N. Y.
41	Earl Jefferson Hamilton	Durham, N. C.
32	Henry Wyman Holmes	Cambridge
34	Edwin Walter Kemmerer	Princeton, N. J.
34	Frank Hyneman Knight	Chicago, Ill.
42	Wassily W. Leontief	Cambridge
36	Roswell Cheney McCrea	New York, N. Y.
34	Robert Morison MacIver	New York, N. Y.
32	Walter Wallace McLaren	Williamstown
36	Malcolm Perrine McNair	Cambridge
32	Leon Carroll Marshall	Chevy Chase, Md.
33	Edward Sagendorph Mason	Cambridge
36	Elton Mayo	Cambridge
34	Richard Stockton Meriam	South Lincoln
34	Harry Alvin Millis	Washington, D. C.
32	Frederick Cecil Mills	New York, N. Y.
31	Wesley Clair Mitchell	New York, N. Y.
34	Arthur Eli Monroe	Cambridge
32	Harold Glenn Moulton	Washington, D. C.
34	Edwin Griswold Nourse	Washington, D. C.
32	William Fielding Ogburn	Chicago, Ill.
33	Robert Ezra Park	Nashville, Tenn.
42	William Andrew Paton	Ann Arbor, Mich.
32	Leo S. Rowe	Washington, D. C.
37	Clyde Orval Ruggles	Cambridge
42	Paul Anthony Samuelson	Cambridge
36	Thomas Henry Sanders	Cambridge
33	Josef Alois Schumpeter	Cambridge
32	Carl Snyder	New York, N. Y.
31	Pitirim Alexandrovich Sorokin	Winchester
41	Francis Trow Spaulding	Cambridge
31	Oliver Mitchell Wentworth Sprague	Cambridge
34	Frederick John Teggart	Berkeley, Cal.
33	William Isaac Thomas	Berkeley, Cal.
37	Harry Rudolph Tosdal	Belmont
31	Donald Skeele Tucker	Belmont
41	Robert Ulich	Cambridge
33	Abbott Payson Usher	Cambridge
34	Jacob Viner	Chicago, Ill.
38	T[homas] North Whitehead	Cambridge
32	John Henry Williams	Cambridge
36	Joseph Henry Willits	New York, N. Y.
34	Leo Wolman	New York, N. Y.
34	Carle Clark Zimmerman	Winchester

Class III, Section IV—*Administration and Affairs*—36

(25) 32	Charles Francis Adams	Concord
39	Chester Irving Barnard	Newark, N. J.
(25) 32	Charles Foster Batchelder	Cambridge
41	Godfrey Lowell Cabot	Boston
42	Donald Kirk David	Winchester
38	Edmund Ezra Day	Ithaca, N. Y.
41	Frederic Adrian Delano	Washington, D. C.
32	Henry Sturgis Dennison	Framingham
(28) 32	William Lusk Webster Field	Milton
39	Ralph Edward Flanders	Springfield, Vt.
38	Horace Sayford Ford	Belmont
35	Jerome Davis Greene	Cambridge
42	Roger Sherman Greene	Worcester
39	Henry Ingraham Harriman	Newton Center
(28) 32	Edward Jackson Holmes	Topsfield
41	Edward Godfrey Huber	Waban
34	Henry Plimpton Kendall	Sharon
32	Thomas William Lamont	New York, N. Y.
39	Morris Evans Leeds	Philadelphia, Pa.
34	Clarence Cook Little	Bar Harbor, Me.
36	Dumas Malone	Belmont
42	Daniel L. Marsh	Boston
33	James Vance May	Watertown
02	Herbert Putnam	Washington, D. C.
(28) 32	Alfred Lawrence Ripley	Andover
34	Erwin Haskell Schell	Cambridge
38	Charles Seymour	New Haven, Conn.
35	Henry Lee Shattuck	Boston
37	Henry Southworth Shaw	Exeter, N. H.
(28) 32	Payson Smith	Orono, Me.
33	Albert Warren Stearns	Billerica
36	Clair Elsmere Turner	Arlington
(24) 32	Edwin Sibley Webster	Brookline
41	Laurence Leathe Winship	South Sudbury
(25) 32	Benjamin Loring Young	Weston
39	Owen D. Young	New York, N. Y.

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32	Michael Joseph Ahern	Weston
33	Gordon Willard Allport	Cambridge
32	James Rowland Angell	Hamden, Conn.
33	John Gilbert Beebe-Center	Swampscott
38	Julius Seelye Bixler	Waterville, Me.
24	Edwin Garrigues Boring	Cambridge
28	Edgar Sheffield Brightman	Newton
31	Henry Addington Bruce	Cambridge
32	Leonard Carmichael	Tufts College
36	Robert Pierce Casey	Providence, R. I.
33	J[ames] McKeen Cattell	Garrison, N. Y.
28	Walter Fenno Dearborn	Cambridge
18	Edmund Burke Delabarre	Providence, R. I.
33	Curt John Ducasse	Providence, R. I.
38	James Everett Frame	Princeton, N. J.
37	Clarence Henry Graham	Providence, R. I.
30	William Henry Paine Hatch	Cambridge
32	William Healy	Boston
21	William Ernest Hocking	Cambridge
35	Clark Leonard Hull	New Haven, Conn.
33	Walter Samuel Hunter	Providence, R. I.
28	Albert Cornelius Knudson	Cambridge
32	Karl Spencer Lashley	Orange Park, Fla.
29	Clarence Irving Lewis	Lexington
33	Lee Sullivan McCollester	Tufts College
42	Richard Peter McKeon	Chicago, Ill.
10	Edward Caldwell Moore	Cambridge
35	Henry Alexander Murray, Jr.	Boston
32	Arthur Darby Nock	Cambridge
32	William Cardinal O'Connell	Boston
28	Johnson O'Connor	Boston

17	Charles Edwards Park	Boston
33	Carroll Cornelius Pratt	New Brunswick, N. J.
41	James Bissett Pratt	Williamstown
30	James Hugh Ryan	Omaha, Neb.
31	Henry Knox Sherrill	Boston
27	Willard Learoyd Sperry	Cambridge
29	Russell Henry Stafford	Brookline
34	Lewis Madison Terman	Stanford University, Cal.
34	Edward Lee Thorndike	New York, N. Y.
37	Louis Leon Thurstone	Chicago, Ill.
28	Henry Bradford Washburn	Cambridge
17	John Broadus Watson	New York, N. Y.
33	Frederic Lyman Wells	Newton Highlands
35	Robert Sessions Woodworth	New York, N. Y.
15	Robert Mearns Yerkes	New Haven, Conn.

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18	Charles McLean Andrews	New Haven, Conn.
41	Warren Ortman Ault	Waban
28	James Phinney Baxter, 3d	Williamstown
23	Carl Lotus Becker	Ithaca, N. Y.
27	Robert Pierpont Blake	Cambridge
12	Franz Boas	Grantwood, N. J.
39	Crane Brinton	Cambridge
(25) 32	William Brooks Cabot	Boston
34	Clarence Gordon Campbell	New York, N. Y.
12	George Henry Chase	Cambridge
21	Max Farrand	Bar Harbor, Me.
21	William Scott Ferguson	Cambridge
38	Allyn Bailey Forbes	Cambridge
33	Henry Thatcher Fowler	Harmony, R. I.
38	Claude Moore Fuess	Andover
18	Evarts Boutell Greene	New York, N. Y.
14	Bert Hodge Hill	Athens, Greece
27	Earnest Albert Hooton	Cambridge
33	Halford Lancaster Hoskins	Tufts College
15	Aleš Hrdlička	Washington, D. C.
12	Alfred Louis Kroeber	Berkeley, Cal.
15	Kirsopp Lake	So. Pasadena, Cal.
22	George LaPiana	Cambridge
32	Waldo Gifford Leland	Washington, D. C.
41	William E. Lingelbach	Philadelphia, Pa.
20	Charles Howard McIlwain	Belmont
14	Roger Bigelow Merriman	Cambridge
38	Stewart Mitchell	Gloucester
15	Samuel Eliot Morison	Boston
34	Robert Henry Pfeiffer	Cambridge
34	David Moore Robinson	Baltimore, Md.
23	Michael Ivanovich Rostovtzeff	New Haven, Conn.
27	George Sarton	Cambridge
38	Bernadotte Everly Schmitt	Chicago, Ill.
36	Donald Scott	Cambridge
34	Theodore Leslie Shear	Princeton, N. J.
26	Herbert Joseph Spinden	Brooklyn, N. Y.
32	Charles Holt Taylor	Cambridge
11	Alfred Marston Tozzer	Cambridge
39	Henry Rouse Viets	Dedham
20	Clark Wissler	New York, N. Y.

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31	Edward Cooke Armstrong	Princeton, N. J.
33	William Nickerson Bates	Philadelphia, Pa.
35	Charles Henry Beeson	Chicago, Ill.
33	Campbell Bonner	Ann Arbor, Mich.
35	Robert Johnson Bonner	Chicago, Ill.
41	Giuseppe Antonio Borgese	Chicago, Ill.
21	Carl Darling Buck	Chicago, Ill.
18	Edward Capps	Princeton, N. J.
20	Walter Eugene Clark	Cambridge
32	Ronald Salmon Crane	Chicago, Ill.
32	Morris William Croll	Princeton, N. J.
31	Samuel Hazzard Cross	Cambridge
20	Franklin Edgerton	New Haven, Conn.
40	Serge Elisséeff	Cambridge
21	Frank Edgar Farley	Middletown, Conn.
14	Jeremiah Denis Mathias Ford	Cambridge
30	James Geddes, Jr.	Brookline
16	Louis Herbert Gray	New York, N. Y.
25	William Chase Greene	Cambridge
13	Charles Burton Gulick	Cambridge
19	Roy Kenneth Hack	Cincinnati, Ohio
34	Austin Morris Harmon	New Haven, Conn.
31	Raymond Dexter Havens	Baltimore, Md.
38	Richmond Laurin Hawkins	Cambridge
18	George Lincoln Hendrickson	New Haven, Conn.
17	William Guild Howard	Cambridge
15	Carl Newell Jackson	Snowville, N. H.
40	Werner Wilhelm Jaeger	Watertown
13	James Richard Jewett	Cambridge
32	(Ralph) Hayward Keniston	Ann Arbor, Mich.
34	Roland Grubb Kent	Wynnewood, Pa.
33	Hans Kurath	Providence, R. I.
39	Henry Carrington Lancaster	Baltimore, Md.
32	Ernest Felix Langley	Cambridge
33	Ivan Mortimer Linforth	Berkeley, Cal.
11	Albert Matthews	Boston
35	Benjamin Dean Meritt	Princeton, N. J.
28	William Albert Nitze	Chicago, Ill.
32	George Rapall Noyes	Berkeley, Cal.
34	William Abbott Oldfather	Urbana, Ill.
33	Howard Rollin Patch	Northampton
32	Arthur Stanley Pease	Cambridge
35	Henry Washington Prescott	Chicago, Ill.
13	Edward Kennard Rand	Cambridge
11	Fred Norris Robinson	Cambridge
38	Hyder Edward Rollins	Cambridge
31	Robert Kilburn Root	Princeton, N. J.
35	Henry Arthur Sanders	Ann Arbor, Mich.
18	Rudolph Schevill	Berkeley, Cal.
32	Horatio Elwin Smith	New York, N. Y.
40	Edgar Howard Sturtevant	New Haven, Conn.
39	John Strong Perry Tatlock	Berkeley, Cal.
32	William Thomson	So. Lincoln
11	Charles Cutler Torrey	New Haven, Conn.
33	George Benson Weston	Cambridge
30	Ernest Hatch Wilkins	Oberlin, Ohio
33	Harry Austryn Wolfson	Cambridge
39	William Hoyt Worrell	Ann Arbor, Mich.
33	Karl Young	New Haven, Conn.

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31	Stephen Vincent Benét	New York, N. Y.
26	Frank Weston Benson	Salem
32	(William) Welles Bosworth	New York, N. Y.
42	John Nash Douglas Bush	Cambridge
33	John Alden Carpenter	Chicago, Ill.
32	Chalmers Dancy Clifton	Westport, Conn.
32	Kenneth John Conant	Cambridge
34	Charles Jay Connick	Newtonville
29	Charles Townsend Copeland	Cambridge
[17] 30	Ralph Adams Cram	Boston
34	Samuel Foster Damon	Providence, R. I.
41	Archibald Thompson Davison	Lincoln
32	George Harold Edgell	Cambridge
21	William Emerson	Cambridge
33	Carl Engel	New York, N. Y.
30	John Erskine	New York, N. Y.
10	Arthur Fairbanks	Hanover, N. H.
18	Edward Waldo Forbes	Cambridge
31	Robert Frost	South Shaftsbury, Vt.
27	Wallace Goodrich	Boston
36	William Clifford Heilman	Cambridge
29	Edward Burlingame Hill	Cambridge
31	Robert Silliman Hillyer	Cambridge
27	Charles Hopkinson	Manchester
12	Mark Antony DeWolfe Howe	Boston
38	Joseph Hudnut	Boston
18	Archer Milton Huntington	New York, N. Y.
31	Henry James	New York, N. Y.
38	Howard Mumford Jones	Cambridge
42	Otto Kinkeldey	Ithaca, N. Y.
33	Leo Rich Lewis	Tufts College
20	John Ellerton Lodge	Washington, D. C.
21	John Livingston Lowes	Cambridge
21	Charles Donagh Maginnis	Brookline
31	Paul Manship	New York, N. Y.
31	Daniel Gregory Mason	New York, N. Y.
31	Frank Jewett Mather	Washington Crossing, Pa.
31	Kenneth Ballard Murdock	Cambridge
14	William Allan Neilson	Falls Village, Conn.
28	Curtis Hidden Page	Gilmanton, N. H.
21	William Lyon Phelps	New Haven, Conn.
(24) 32	Anthony John Philpott	Arlington
41	Walter Hamor Piston, Jr.	Belmont
21	Chandler Rathfon Post	Cambridge
22	Paul Joseph Sachs	Cambridge
14	Ellery Sedgwick	Boston
19	Henry Dwight Sedgwick	Dedham
33	David Stanley Smith	Woodbridge, Conn.
39	Francis Henry Taylor	New York, N. Y.
39	Karl Ephraim Weston	Williamstown
38	Grenville Lindall Winthrop	Lenox
22	Charles Henry Conrad Wright	Cambridge

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22	Sir Arthur Stanley Eddington	Cambridge, England
34	Ronald Aylmer Fisher	Harpenden, Herts
20	Jacques Salomon Hadamard	Princeton, N. J.
21	Godfrey Harold Hardy	Cambridge, England
27	Ejnar Hertzsprung	Leyden
15	Charles Jean de la Vallée Poussin	Louvain
29	Hermann Weyl	Princeton, N. J.

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29	Vilhelm Frimann Koren Bjerknes	Oslo
24	Albert Einstein	Princeton, N. J.
29	James Franck	Chicago, Ill.
29	Abram F. Joffé	Leningrad
28	Friedrich Paschen	Charlottenburg
14	Max Planck	Berlin

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29	Johannes N. Brönsted	Copenhagen
27	Peter Debye	Ithaca, N. Y.
33	Jaroslav Heyrovsky	Prague
33	Fritz Paneth	Durham
38	Leopold Ruzicka	Zürich
38	Nevil Vincent Sidgwick	Oxford
29	Heinrich Wieland	Munich

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36	Edward Victor Appleton	London
34	Luigi Lombardi	Rome
29	Ludwig Prandtl	Göttingen
29	Emil Probst	Oxford
29	Aurel Stodola	Zürich
31	Karl Willy Wagner	Berlin

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17	Frank Dawson Adams	Montreal
36	Raoul Blanchard	Grenoble, France
29	Léon William Collet	Geneva
34	Arthur Holmes	Durham
22	Emmanuel de Margerie	Paris
21	Gustaf Adolf Frederik Molengraaff	Delft
18	Sir William Napier Shaw	London

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32	Frederick Orpen Bower	Ripon
31	Ludwig Diels	Berlin
32	Kingo Miyabe	Sapporo, Japan
42	Lorenzo Raimundo Parodi	Buenos Aires
29	Otto Renner	Jena
35	Sir William Wright Smith	Edinburgh

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38	Edgar Douglas Adrian	Cambridge, England
38	Sir Joseph Barcroft	Cambridge, England
20	Maurice Caullery	Paris
38	Emmanuel Fauré-Frémiet	Paris
34	Archibald Vivian Hill	London
41	Bernado Alberto Houssay	Buenos Aires
31	August Krogh	Copenhagen
30	Louis Édouard Lapicque	Paris
28	Charles Tate Regan	Feltham, Middlesex
28	Sir D'Arcy Wentworth Thompson	St. Andrews

CLASS II, SECTION IV—*Medicine and Surgery*—7

18	Sir Thomas Barlow, Bart	London
39	Sir Aldo Castellani	Rome
27	Sir Henry Hallett Dale	London
33	Sir Arthur Keith	London
28	Mikinosuke Miyajima	Tokyo
18	Sir Charles Scott Sherrington	Ipswich, England
36	(Jean) Hyacinthe Vincent	Paris

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39	Rt. Hon. Lord Atkin	London
38	William Warwick Buckland	Cambridge, England
38	Mircea Djuvara	Bucharest
27	Léon Duguit	Bordeaux
33	François Geny	Nancy
38	Arthur Lehman Goodhart	Oxford
39	Wilfrid Arthur Greene, Baron Greene	London
39	Sir William Searle Holdsworth	Oxford
33	Hans Kelsen	Cambridge, Mass.
38	Rt. Hon. Lord Macmillan	London
33	Juljusz Makarewicz	Lwów
33	Rudolph Stammler	Wernigerode a. H.
33	Giorgio Del Vecchio	Rome
38	Rt. Hon. Lord Wright	London
38	John C. H. Wu	Hong Kong

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38	Dionisio Anzilotti	Rome
32	Paul Claudel	Paris
32	Hu Shih	Washington, D. C.
38	Kenzo Takayanagi	Tokyo

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32	Arthur Lyon Bowley	Haslemere, Surrey
34	Gustav Cassel	Djursholm, Sweden
39	Henry Clay	Kenley, Surrey
35	Luigi Einaudi	Turin
32	Ralph George Hawtrey	London
35	John Maynard Keynes, Baron Keynes	Cambridge, England
35	René Maunier	Paris
28	Arthur Cecil Pigou	Cambridge, England
32	Charles Rist	Fraisses (Loire)
35	S. Rudolph Steinmetz	Amsterdam
34	Peter B. Struve	Belgrade

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33	Gösta A. Bagge	Stockholm
38	Heinrich Brüning	Cambridge, Mass.
38	B. Seebohm Rowntree	North Dean, Bucks

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36	Miguel Asín y Palacios	Madrid
28	Benedetto Croce	Naples
29	Étienne Gilson	Melun
28	Edmund Husserl	Freiburg i. B.
32	Pierre Janet	Paris
28	Wolfgang Köhler	Swarthmore, Pa.
37	Henri Piéron	Paris

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33	Rafael Altamira y Crevea	Madrid
36	Marcel Aubert	Paris
29	Godfrey R. Benson, Baron Charnwood	London
33	Friedrich Meinecke	Berlin-Dahlem
40	Martin Persson Nilsson	Lund
30	Sir Aurel Stein	Srinagar, Kashmir
31	George Macaulay Trevelyan	Cambridge, England

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09	Hermann Georg Jacobi	Bonn
36	Paul Kretschmer	Vienna
32	Paul Mazon	Paris
[12] 28	Hanns Oertel	Munich
17	Ramón Menéndez Pidal	Madrid
32	Frederick William Thomas	Oxford

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40	Fernand Baldensperger	Los Angeles, Cal.
30	Alfredo Casella	Rome
23	Henry Guy	Grenoble
29	Paul Hazard	Paris
40	Paul Hindemith	New Haven, Conn.
34	Serge Koussevitzky	Boston
27	Gilbert Murray	Oxford
31	Edgar Allison Peers	Liverpool
27	Henri Rabaud	Paris
41	Jan Sibelius	Helsinki
40	Igor Stravinsky	Paris

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Delabarre, E. B. F, IV: 1
Delano, F. A. F, III: 4
Den Hartog, J. P. F, I: 4
Denjoy, A. FHM, I: 1
Dennett, T. F, III: 2
Dennison, H. S. F, III: 4
Detwiler, S. R. F, II: 3
Dewey, D. R. F, III: 3
Dewing, A. S. F, III: 3
Dickinson, J. F, III: 1
Dickson, L. E. F, I: 1
Diels, L. FHM, II: 2
Dillon, T. H. F, I: 4
Djuvara, M. FHM, III: 1
Dodge, B. O. F, II: 2
Dodge, R. G. F, III: 1
Doering, C. R. F, III: 3
Donham, W. B. F, III: 3
Douglas, J. F, I: 1
Draper, C. S. F, I: 4
Drisko, W. J. F, I: 2
Du Bois, E. F. F, II: 4
Ducasse, C. J. F, IV: 1
Duff, A. W. F, I: 2
Duguit, L. FHM, III: 1
Duncan, J. C. F, I: 1
Dunn, G. F, I: 4
Durand, W. F. F, I: 4
Eames, A. J. F, II: 2
Ebersole, J. F. F, III: 3
Eddington, Sir A. S. FHM, I: 1
Edgell, G. H. F, IV: 4
Edgerton, F. F, IV: 3
Edsall, J. T. F, I: 3
Einaudi, L. FHM, III: 3
Einstein, A. FHM, I: 2
Elisséeff, S. F, IV: 3
Ellis, H. S. F, III: 3
Emerson, R. A. F, II: 2
Emerson, W. F, IV: 4
Engel, C. F, IV: 4
Erskine, J. F, IV: 4
Esselen, G. J. F, I: 3
Evans, A. W. F, II: 2
Evans, G. C. F, I: 1
Evans, H. M. F, II: 3
Evans, W. L. F, I: 3
Ewell, A. W. F, I: 2
Fair, G. M. F, I: 4
Fairbanks, A. F, IV: 4
Fairchild, F. R. F, III: 3
Farley, F. E. F, IV: 3
Farnsworth, H. E. F, I: 2
Farrand, M. F, IV: 2
Faull, J. H. F, II: 2
Fauré-Frémiet, E. FHM, II: 3
Fay, F. H. F, I: 4
Fay, S. B. F, III: 2
Ferguson, W. S. F, IV: 2
Fergusson, S. P. F, II: 1
Fernald, M. L. F, II: 2
Fetter, F. A. F, III: 3
Field, F. T. F, III: 1
Field, W. L. W. F, III: 4
Fieser, L. F. F, I: 3
Fisher, I. F, III: 3
Fisher, R. A. FHM, I: 1
Fiske, C. H. F, II: 3
Fitz, R. F, II: 4
Flanders, R. E. F, III: 4
Flexner, S. F, II: 4
Forbes, A. F, II: 3
Forbes, A. B. F, IV: 2
Forbes, E. W. F, IV: 4
Forbes, G. S. F, I: 3
Forbes, W. C. F, III: 2
Ford, H. S. F, III: 4
Ford, J. F, III: 3
Ford, J. D. M. F, IV: 3
Fowler, H. T. F, IV: 2
Fox, P. F, I: 1
Frame, J. E. F, IV: 1
Franck, J. FHM, I: 2
Franklin, P. F, I: 1
Freeman, R. E. F, III: 3
Frost, R. F, IV: 4
Fuess, C. M. F, IV: 2
Fulton, J. F. F, II: 3
Furniss, E. S. F, III: 2
Gamble, J. L. F, II: 4
Gay, E. F. F, III: 3
Geddes, J., Jr. F, IV: 3
Geny, F. FHM, III: 1
Gibson, R. F, II: 1
Gilboy, G. F, I: 4
Gilson, E. FHM, IV: 1
Glueck, S. F, III: 3
Goldthwait, J. W. F, II: 1
Goodale, J. L. F, II: 4
Goodhart, A. L. FHM, III: 1
Goodrich, H. F. F, III: 1
Goodrich, W. F, IV: 4
Goodwin, H. M. F, I: 2
Graham, C. H. F, IV: 1
Graton, L. C. F, II: 1
Gray, L. H. F, IV: 3
Green, T. F. F, III: 1
Greene, E. B. F, IV: 2
Greene, J. D. F, III: 4
Greene, R. S. F, III: 4
Greene, Baron. FHM, III: 1
Greene, W. C. F, IV: 3

Gregory, H. E. F, II: 1
Gregory, W. K. F, II: 3
Grew, J. C. F, III: 2
Grinnell, F. W. F, III: 1
Griswold, E. N. F, III: 1
Gulick, C. B. F, IV: 3
Guy, H. FHM, IV: 4
Haberler, G. F, III: 3
Hack, R. K. F, IV: 3
Hadamard, J. S. FHM, I: 1
Haertlein, A. F, I: 4
Haig, R. M. F, III: 3
Haines, C. G. F, III: 2
Hall, J. L. F, III: 1
Hamilton, E. J. F, III: 3
Hand, A. N. F, III: 1
Hand, L. F, III: 1
Hardy, A. C. F, I: 2
Hardy, G. H. FHM, I: 1
Harmon, A. M. F, IV: 3
Harno, A. J. F, III: 1
Harper, R. A. F, II: 2
Harriman, H. I. F, III: 4
Harris, L. F, I: 3
Harrison, G. R. F, I: 2
Harrison, R. G. F, II: 4
Hart, A. B. F, III: 2
Hastings, A. B. F, I: 3
Hatch, W. H. P. F, IV: 1
Havens, R. D. F, IV: 3
Hawkins, R. L. F, IV: 3
Hawtrey, R. G. FHM, III: 3
Hayes, H. V. F, I: 2
Hazard, P. FHM, IV: 4
Hazen, H. L. F, I: 4
Healy, W. F, IV: 1
Heilman, W. C. F, IV: 4
Hendrickson, G. L. F, IV: 3
Hertzsprung, E. FHM, I: 1
Heyrovsky, J. FHM, I: 3
Hill, A. V. FHM, II: 3
Hill, B. H. F, IV: 2
Hill, E. B. F, IV: 4
Hille, E. F, I: 1
Hillyer, R. S. F, IV: 4
Hindemith, P. FHM, IV: 4
Hisaw, F. L. F, II: 3
Hitchcock, F. L. F, I: 1
Hoadley, L. F, II: 3
Hoagland, H. F, II: 3
Hockett, R. C. F, I: 3
Hocking, W. E. F, IV: 1
Holborn, H. F, III: 2
Holcombe, A. N. F, III: 2
Holdworth, Sir W. S. FHM, III: 1
Holmes, A. FHM, II: 1
Holmes, E. J. F, III: 4
Holmes, H. W. F, III: 3
Holmes, S. J. F, II: 3
Hooton, E. A. F, IV: 2
Hopkinson, C. F, IV: 4
Horwood, M. P. F, I: 4
Hoskins, H. L. F, IV: 2
Hoskins, R. G. F, II: 3
Houssay, B. A. FHM, II: 3
Hovgaard, W. F, I: 4
Howard, L. O. F, II: 3
Howard, W. G. F, IV: 3
Howe, M. A. DeW. F, IV: 4
Howe, P. R. F, II: 4
Howell, W. H. F, II: 4
Hrdlička, A. F, IV: 2
Hu Shih. FHM, III: 2
Hubbard, J. C. F, I: 2
Huber, E. G. F, III: 4
Hudnut, J. F, IV: 4
Hudson, M. O. F, III: 2
Hughes, C. E. F, III: 1
Hull, C. L. F, IV: 1
Hull, G. F. F, I: 2
Hume, E. E. F, II: 4
Humphreys, W. J. F, II: 1
Hunsaker, J. C. F, I: 4
Hunt, F. V. F, I: 2
Hunt, R. F, II: 4
Hunter, W. S. F, IV: 1
Huntington, A. M. F, IV: 4
Huntington, E. F, II: 1
Huntington, E. V. F, I: 1
Huntress, E. H. F, I: 3
Husserl, E. FHM, IV: 1
Ives, J. E. F, I: 2
Jack, J. G. F, II: 2
Jack, J. R. F, I: 4
Jackson, C. N. F, IV: 3
Jackson, D. F, I: 1
Jackson, D. C. F, I: 4
Jackson, H., Jr. F, II: 4
Jackson, R. T. F, II: 1
Jacobi, H. G. FHM, IV: 3
Jaeger, W. W. F, IV: 3
Jaggar, T. A. F, II: 1
James, H. F, IV: 4
Janet, P. FHM, IV: 1
Jellinek, E. M. F, I: 1
Jennings, H. S. F, II: 3
Jennings, W. L. F, I: 3
Jepson, W. L. F, II: 2
Jessup, P. C. F, III: 2
Jewett, F. B. F, I: 4
Jewett, J. R. F, IV: 3
Joffé, A. F. FHM, I: 2
Johnson, D. W. F, II: 1
Johnson, L. J. F, I: 4
Johnson, M. M. F, III: 1
Johnston, I. M. F, II: 2
Jones, D. F. F, II: 2
Jones, G. F, I: 3
Jones, H. M. F, IV: 4
Joslin, E. P. F, II: 4
Keenan, J. H. F, I: 4
Keith, Sir A. FHM, II: 4
Keith, A. F, II: 1
Kelsen, H. FHM, III: 1
Kemble, E. C. F, I: 2
Kemmerer, E. W. F, III: 3
Kendall, H. P. F, III: 4
Keniston, H. F, IV: 3
Kent, N. A. F, I: 2
Kent, R. G. F, IV: 3
Keyes, F. G. F, I: 3
Keynes, Baron. FHM, III: 3
Kinkeldey, O. F, IV: 4
Kistiakowsky, G. B. F, I: 3
Knight, F. H. F, III: 3
Knudson, A. C. F, IV: 1
Köhler, W. FHM, IV: 1
Kofoid, C. A. F, II: 3
Koussevitzky, S. FHM, IV: 4
Kraus, C. A. F, I: 3
Kretschmer, P. FHM, IV: 3
Kroeber, A. L. F, IV: 2
Krogh, A. FHM, II: 3
Kurath, H. F, IV: 3
Lake, K. F, IV: 2
Lamb, A. B. F, I: 3
Lamont, T. W. F, III: 4
Lampland, C. O. F, I: 1
Lancaster, H. C. F, IV: 3
Landis, J. M. F, III: 1
Lane, A. C. F, II: 1
Langley, E. F. F, IV: 3
Langmuir, I. F, I: 3
La Piana, G. F, IV: 2
Lapicque, L. E. FHM, II: 3
Larsen, E. S. F, II: 1
Lashley, K. S. F, IV: 1
Lawrence, E. O. F, I: 2
Lawrence, R. R. F, I: 4
Lawrence, W. H. F, I: 4
Lawson, A. C. F, II: 1
Lee, R. I. F, II: 4
Leeds, M. E. F, III: 4
Lefavour, H. F, I: 2
Leith, C. K. F, II: 1
Leland, W. G. F, IV: 2
Leontief, W. W. F, III: 3
Lessells, J. M. F, I: 4
Levine, S. A. F, II: 4
Lewis, C. I. F, IV: 1
Lewis, F. T. F, II: 3
Lewis, G. N. F, I: 3
Lewis, L. R. F, IV: 4
Lewis, W. K. F, I: 3
Lillie, F. R. F, II: 3
Lillie, R. S. F, II: 3
Lindsay, R. B. F, I: 2
Linforth, I. M. F, IV: 3
Lingelbach, W. E. F, IV: 2
Little, C. C. F, III: 4

Livingston, B. E. F, II: 2
Locke, E. A. F, II: 4
Lodge, J. E. F, IV: 4
Lombardi, L. FHM, I: 4
Longcope, W. T. F, II: 4
Lowell, A. L. F, III: 2
Lowes, J. L. F, IV: 4
Lull, R. S. F, II: 3
Lund, F. B. F, II: 4
Luyten, W. J. F, I: 1
Lyman, T. F, I: 2
McAdie, A. G. F, II: 1
McCollester, L. S. F, IV: 1
McCrea, R. C. F, III: 3
McEwen, G. F. F, II: 1
McIlwain, C. H. F, IV: 2
MacInnes, D. A. F, I: 3
MacIver, R. M. F, III: 3
McKeehan, L. W. F, I: 2
McKeon, R. P. F, IV: 1
McLaren, W. W. F, III: 3
McLaughlin, D. H. F, II: 1
Macmillan, Lord. FHM, III: 1
McNair, M. P. F, III: 3
Macneil, S. F, III: 1
MacNider, W. de B. F, II: 4
Maginnis, C. D. F, IV: 4
Magruder, C. F, III: 1
Main, C. T. F, I: 4
Makarewicz, J. FHM, III: 1
Malone, D. F, III: 4
Mangelsdorf, P. C. F, II: 2
Manship, P. F, IV: 4
Margerie, E. de. FHM, II: 1
Mark, E. L. F, II: 3
Mark, K. L. F, I: 3
Marks, L. S. F, I: 4
Marsh, D. L. F, III: 4
Marshall, L. C. F, III: 3
Mason, D. G. F, IV: 4
Mason, E. S. F, III: 3
Mather, F. J. F, IV: 4
Mather, K. F. F, II: 1
Mathews, E. B. F, II: 1
Matthews, A. F, IV: 3
Maunier, R. FHM, III: 3
Maxon, W. R. F, II: 2
May, J. V. F, III: 4
Mayo, E. F, III: 3
Mazon, P. FHM, IV: 3
Mead, A. D. F, II: 3
Mead, W. J. F, II: 1
Mees, C. E. K. F, I: 3
Meinecke, F. FHM, IV: 2
Melander, A. L. F, II: 3
Menzel, D. H. F, I: 1
Meriam, R. S. F, III: 3
Meritt, B. D. F, IV: 3
Merriam, C. E. F, III: 2
Merriam, J. C. F, II: 1
Merrill, E. D. F, II: 2
Merriman, R. B. F, IV: 2
Merritt, E. G. F, I: 2
Meyer, K. F. F, II: 3
Milas, N. A. F, I: 3
Miller, G. A. F, I: 1
Miller, G. S. F, II: 3
Miller, J. A. F, I: 1
Miller, W. J. F, II: 1
Millikan, R. A. F, I: 2
Millis, H. A. F, III: 3
Mills, F. C. F, III: 3
Mimno, H. R. F, I: 2
Miner, L. M. S. F, II: 4
Minot, G. R. F, II: 4
Mitchell, S. F, IV: 2
Mitchell, S. A. F, I: 1
Mitchell, W. C. F, III: 3
Mitchell, W. DeW. F, III: 1
Miyabe, K. FHM, II: 2
Miyajima, M. FHM, II: 4
Molengraaff, G. A. F. FHM, II: 1
Monroe, A. E. F, III: 3
Moore, E. C. F, IV: 1
Moore, J. B. F, III: 2
Moreland, E. L. F, I: 4
Morgan, E. M. F, III: 1
Morgan, T. H. F, II: 3
Morison, S. E. F, IV: 2
Moritz, A. R. F, II: 4
Morris, F. K. F, II: 1
Morse, M. F, I: 1
Morse, P. M. F, I: 2
Morton, A. A. F, I: 3
Moss, W. L. F, II: 4
Moulton, F. R. F, I: 1
Moulton, H. G. F, III: 3
Mueller, E. F, I: 3
Mueller, J. H. F, II: 4
Muller, H. J. F, II: 3
Munro, W. B. F, III: 2
Murdock, K. B. F, IV: 4
Murray, G. FHM, IV: 4
Murray, H. A., Jr. F, IV: 1
Neilson, W. A. F, IV: 4
Newhouse, W. H. F, II: 1
Nilsson, M. P. FHM, IV: 2
Nitze, W. A. F, IV: 3
Nock, A. D. F, IV: 1
Nourse, E. G. F, III: 3
Noyes, G. R. F, IV: 3
Noyes, W. A., Jr. F, I: 3
O'Connell, W. H. F, IV: 1
O'Connor, J. F, IV: 1
Oertel, H. FHM, IV: 3
Ogburn, W. F. F, III: 3
Oldenberg, O. F, I: 2
Oldfather, W. A. F, IV: 3
Olmsted, F. L. F, I: 4
Osgood, R. B. F, II: 4
Osterhout, W. J. V. F, II: 2
Page, C. H. F, IV: 4
Page, L. F, I: 2
Palmer, W. W. F, II: 4
Paneth, F. FHM, I: 3
Park, C. E. F, IV: 1
Park, C. F. F, I: 4
Park, R. E. F, III: 3
Parker, G. H. F, II: 3
Parkman, H., Jr. F, III: 1
Parodi, L. R. FHM, II: 2
Paschen, F. FHM, I: 2
Patch, H. R. F, IV: 3
Paton, W. A. F, III: 3
Patterson, R. P. F, III: 1
Pearse, L. F, I: 4
Pease, A. S. F, IV: 3
Peers, E. A. FHM, IV: 4
Peirce, G. J. F, II: 2
Pender, H. F, I: 4
Pepper, G. W. F, III: 1
Pfeiffer, R. H. F, IV: 2
Phelps, W. L. F, IV: 4
Phillips, H. B. F, I: 1
Philpott, A. J. F, IV: 4
Pickard, G. W. F, I: 4
Pidal, R. M. FHM, IV: 3
Pierce, G. W. F, I: 2
Piéron, H. FHM, IV: 1
Pigou, A. C. FHM, III: 3
Pilsbry, H. A. F, II: 3
Pincus, G. F, II: 3
Piston, W. H. F, IV: 4
Planck, M. FHM, I: 2
Poor, C. L. F, I: 1
Post, C. R. F, IV: 4
Pound, R. F, III: 1
Prandtl, L. FHM, I: 4
Pratt, C. C. F, IV: 1
Pratt, F. H. F, II: 3
Pratt, J. B. F, IV: 1
Pratt, J. H. F, II: 4
Prescott, H. W. F, IV: 3
Prescott, S. C. F, I: 3
Prest, W. M. F, III: 1
Probst, E. FHM, I: 4
Purves, C. B. F, I: 2
Putnam, H. F, III: 4
Putnam, T. J. F, II: 4
Qua, S. E. F, III: 1
Quinby, W. C. F, II: 4
Rabaud, H. FHM, IV: 4
Rabi, I. I. F, I: 2
Rand, E. K. F, IV: 3
Rand, H. W. F, II: 3
Rapport, D. F, II: 3
Raymond, P. E. F, II: 1
Redfield, A. C. F, II: 3
Regan, C. T. FHM, II: 3
Rehder, A. F, II: 2

Renner, O. FHM, II: 2
Richards, A. N. F, II: 3
Richards, R. H. F, I: 3
Richardson, R. G. D. F, I: 1
Riddle, O. F, II: 3
Ripley, A. L. F, III: 4
Rist, C. FHM, III: 3
Ritter, W. E. F, II: 3
Robinson, D. M. F, IV: 2
Robinson, F. N. F, IV: 3
Rogers, A. F. F, II: 1
Rollins, H. E. F, IV: 3
Romer, A. S. F, II: 3
Root, R. K. F, IV: 3
Rosanoff, M. A. F, I: 3
Rosenblueth, A. F, II: 4
Rossby, C. G. A. F, II: 1
Rostovtzeff, M. I. F, IV: 2
Rowe, L. S. F, III: 3
Rowntree, B. S. FHM, III: 4
Rüdenberg, R. F, I: 4
Ruggles, A. H. F, II: 4
Ruggles, O. C. F, III: 3
Russell, F. F. F, II: 4
Russell, G. E. F, I: 4
Russell, H. N. F, I: 1
Ruthven, A. G. F, II: 3
Ruzicka, L. FHM, I: 3
Ryan, J. H. F, IV: 1
Sachs, P. J. F, IV: 4
Salter, W. T. F, II: 4
Salvemini, G. F, III: 2
Samuelson, P. A. F, III: 3
Sanders, H. A. F, IV: 3
Sanders, T. H. F, III: 3
Sarton, G. F, IV: 2
Sax, K. F, II: 2
Sayles, R. W. F, II: 1
Sayre, F. B. F, III: 1
Scatchard, G. F, I: 3
Schaller, W. T. F, II: 1
Schell, E. H. F, III: 4
Schevill, R. F, IV: 3
Schlesinger, F. F, I: 1
Schmitt, B. E. F, IV: 2
Schmitt, F. O. F, II: 3
Schuchert, C. F, II: 1
Schumb, W. C. F, I: 3
Schumpeter, J. A. F, III: 3
Scott, A. W. F, III: 1
Scott, D. F, IV: 2
Scott, J. B. F, III: 1
Scott, W. B. F, II: 1
Sedgwick, E. F, IV: 4
Sedgwick, H. D. F, IV: 4
Sellards, A. W. F, II: 4
Setchell, W. A. F, II: 2
Seymour, C. F, III: 4
Shapley, H. F, I: 1
Shattuck, G. C. F, II: 4
Shattuck, H. L. F, III: 4
Shaw, H. S. F, III: 4
Shaw, Sir W. N. FHM, II: 1
Shear, T. L. F, IV: 2
Sherrill, H. K. F, IV: 1
Sherrill, M. S. F, I: 3
Sherrington, Sir C. S. FHM, II: 4
Shimer, H. W. F, II: 1
Sibelius, J. FHM, IV: 4
Sidgwick, N. V. FHM, I: 3
Simpson, S. P. F, III: 1
Sinnott, E. W. F, II: 2
Slater, J. C. F, I: 2
Slipher, V. M. F, I: 1
Slocum, F. F, I: 1
Smith, D. S. F, IV: 4
Smith, G. M. F, II: 2
Smith, H. E. F, IV: 3
Smith, H. M. F, I: 3
Smith, L. B. F, I: 3
Smith, P. F, III: 4
Smith, Sir W. W. FHM, II: 2
Smyth, H. L. F, I: 4
Snyder, C. F, III: 3
Snyder, V. F, I: 1
Soderberg, R. C. F, I: 4
Sollmann, T. H. F, II: 4
Sorokin, P. A. F, III: 3
Spaulding, F. T. F, III: 3
Sperry, W. L. F, IV: 1
Spinden, H. J. F, IV: 2
Spofford, C. M. F, I: 4
Sprague, O. M. W. F, III: 3
Stafford, R. H. F, IV: 1
Stakman, E. C. F, II: 2
Stammler, R. FHM, II: 1
Sterns, A. W. F, III: 4
Stebbins, J. F, I: 1
Stein, Sir A. FHM, IV: 2
Steinmetz, S. R. FHM, III: 3
Stetson, H. T. F, I: 1
Stevens, J. F. F, I: 4
Stewart, G. W. F, I: 2
Stock, C. F, II: 1
Stodola, A. FHM, I: 4
Stone, H. F. F, III: 1
Stone, J. S. F, I: 2
Stravinsky, I. FHM, IV: 4
Street, J. C. F, I: 2
Strong, R. P. F, II: 4
Struik, D. J. F, I: 1
Struve, O. F, I: 1
Struve, P. B. FHM, III: 3
Sturtevant, E. H. F, IV: 3
Swan, T. W. F, III: 1
Takayanagi, K. FHM, III: 1
Talbot, F. B. F, II: 4
Tamarkin, J. D. F, I: 1
Tatlock, J. S. P. F, IV: 3
Taylor, C. H. F, IV: 2
Taylor, F. H. F, IV: 4
Teggart, F. J. F, III: 3
Terman, L. M. F, IV: 1
Thimann, K. V. F, II: 2
Thomas, F. W. FHM, IV: 3
Thomas, T. H. F, III: 2
Thomas, W. I. F, III: 3
Thompson, Sir D'A. W. FHM, II: 3
Thompson, M. deK. F, I: 2
Thomson, W. F, IV: 3
Thorndike, E. L. F, IV: 1
Thurston, E. S. F, III: 1
Thurstone, L. L. F, IV:1
Tolman, R. C. F, I: 3
Torrey, C. C. F, IV: 3
Tosdal, H. R. F, III: 3
Tozzer, A. M. F, IV: 2
Trelease, W. F, II: 2
Trevelyan, G. M. FHM, IV: 2
Tucker, D. S. F, III: 3
Turner, C. E. F, III: 4
Tyzzer, E. E. F, II: 4
Ulich, R. F, III: 3
Urey, H. C. F, I: 3
Usher, A. P. F, III: 3
Vallarta, M. S. F, I: 2
Vallée Poussin, C. J. de la. FHM, I: 1
Van de Graaff, R. J. F, I: 2
Van Vleck, J. H. F, I: 2
Vaughan, T. W. F, II: 1
Veblen, O. F, I: 1
Vecchio, G. Del. FHM, III: 1
Verhoeff, F. H. F, II: 4
Viets, H. R. F, IV: 2
Vincent, J. H. FHM, II: 4
Viner, J. F, III: 3
Wagner, K. W. FHM, I: 4
Walsh, J. L. F, I: 1
Warner, E. P. F, I: 4
Warren, B. E. F, I: 2
Warren, B. W. F, III: 1
Warren, C. H., F, II: 1
Warren, J. F' III: 1
Washburn, H. B. F, IV: 1
Watson, J. B. F, IV: 1
Wearn, J. T. F, II: 4
Weatherby, C. A. F, II: 2
Webster, D. L. F, I: 2
Webster, E. S. F, III: 4
Weiser, H. B. F, I: 3
Wells, F. L. F, IV: 1
Westergaard, H. M. F, I: 4
Weston, G. B. F, IV: 3
Weston, K. E. F, IV: 4
Weston, R. S. F, I: 4
Weston, W. H., Jr. F, II: 2
Wetmore, R. H. F, II: 2
Weyl, H. FHM, I: 1
Weysse, A. W. F, II: 3
Whipple, F. L. F, I: 1

White, P. D.	F, II: 4
Whitehead, A. N.	F, I: 1
Whitehead, T. N.	F, III: 3
Whitlock, H. P.	F, II: 1
Whitman, E. A.	F, III: 1
Whitmore, F. C.	F, I: 3
Whitney, W. R.	F, I: 3
Whittlesey, D. S.	F, II: 1
Widder, D. V.	F, I: 1
Wieland, H.	FHM, I: 3
Wilkins, E. H.	F, IV: 3
Williams, J. H.	F, III: 3
Williams, R. S.	F, I: 3
Willis, B.	F, II: 1
Willits, J. H.	F, III: 3
Willoughy, W. F.	F, III: 2
Willoughby, W. W.	F, III: 2
Wilson, E. B.	F, I: 2
Wilson, G. G.	F, III: 2
Winship, L. L.	F, III: 4
Winthrop, G. L.	F, IV: 4
Wislocki, G. B.	F, II: 3
Wissler, C.	F, IV: 2
Wolbach, S. B.	F, II: 4
Wolfson, H. A.	F, IV: 3
Wolman, L.	F, III: 3
Wood, R. W.	F, I: 2
Woodworth, R. S.	F, IV: 1
Worcester, J. R.	F, I: 4
Worrall, D. E.	F, I: 3
Worrell, W. H.	F, IV: 3
Wright, Lord.	FHM, III: 1
Wright, C. H. C.	F, IV: 4
Wright, F. E.	F, II: 1
Wright, Q.	F, III: 2
Wu, J. C. H.	FHM, III: 1
Wulff, J.	F, I: 4
Wyman, J., Jr.	F, II: 3
Yeomans, H. A.	F, III: 2
Yerkes, R. M.	F, IV: 1
Young, B. L.	F, III: 4
Young, K.	F, IV: 3
Young, O. D.	F, III: 4
Young, R. C.	F, I: 3
Zeleny, J.	F, I: 2
Zimmerman, C. C.	F, III: 3
Zworykin, V. K.	F, I: 4

STATUTES AND STANDING VOTES.

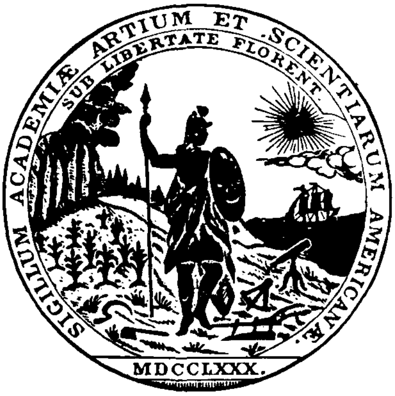
STATUTES.

Adopted November 8, 1911: *amended May* 8, 1912, *January* 8, *and May* 14, 1913, *April* 14, 1915, *April* 12, 1916, *April* 10, 1918, *May* 14, 1919, *February* 8, *April* 12, *and December* 13, 1922, *February* 14, *March* 14, *and October* 10, 1923, *March* 10, 1926, *May* 9, 1928, *April* 8 *and November* 11, 1931, *April* 12, 1933, *February* 14, 1934, *December* 14, 1938, *January* 11, *April* 12, 1939, *May* 8. 1940, *and May* 14, 1941.

CHAPTER I.

THE CORPORATE SEAL.

ARTICLE 1. The Corporate Seal of the Academy shall be as here depicted:


SIGILLUM ACADEMIÆ ARTIUM ET SCIENTIARUM AMERICANÆ.
SUB LIBERTATE FLORENT.
MDCCLXXX.

ARTICLE 2. The Recording Secretary shall have the custody of the Corporate Seal.

See Chap. v, art. 3; chap. vi, art. 2.

CHAPTER II.

FELLOWS AND FOREIGN HONORARY MEMBERS AND DUES.

ARTICLE 1. The Academy consists of Fellows, who are either citizens or residents of the United States of America, and Foreign Honorary Members. They are arranged in four Classes, according to the Arts and Sciences in which they are severally proficient, and each Class is divided into four Sections, namely:

CLASS I. *The Mathematical and Physical Sciences*

Section 1. Mathematics and Astronomy
Section 2. Physics
Section 3. Chemistry
Section 4. Technology and Engineering

CLASS II. *The Natural and Physiological Sciences*

Section 1. Geology, Mineralogy, and Physics of the Globe
Section 2. Botany
Section 3. Zoölogy and Physiology
Section 4. Medicine and Surgery

CLASS III. *The Social Arts*

Section 1. Jurisprudence
Section 2. Government, International Law, and Diplomacy
Section 3. Economics and Sociology
Section 4. Administration and Affairs

CLASS IV. *The Humanities*

Section 1. Theology, Philosophy, and Psychology
Section 2. History, Archæology, and Anthropology
Section 3. Philology
Section 4. The Fine Arts and Belles Lettres

ARTICLE 2. The number of Fellows shall not exceed Eight hundred, of whom not more than Six hundred shall be residents of Massachusetts, nor shall there be more than Two hundred and twenty in any one Class.

ARTICLE 3. The number of Foreign Honorary Members shall not exceed One hundred and thirty. They shall be chosen from among citizens of foreign countries most eminent for their discoveries and attainments in any of the Classes above enumerated. There shall not be more than Thirty-five in any one Class.

ARTICLE 4. If any person, after being notified of his election as Fellow, shall neglect for six months to accept in writing, or, if a Fellow resident within fifty miles of Boston shall neglect to pay his Admission Fee, his election shall be void; and if any Fellow resident within fifty miles of Boston shall neglect to pay his Annual Dues for six months after they are due, provided his attention shall have been called to this Article of the Statutes in the meantime, he shall cease to be a Fellow; but the Council may suspend the provisions of this Article for a reasonable time.

With the previous consent of the Council, the Treasurer may dispense (*sub silentio*) with the payment of the Admission Fee or of the Annual Dues or both whenever he shall deem it advisable. In the case of officers of the Army or Navy who are out of the Commonwealth on duty, payment of the Annual Dues may be waived during such absence if continued during the whole financial year and if notification of such expected absence be sent to the Treasurer. Upon similar notification to the Treasurer, similar exemption may be accorded to Fellows subject to Annual Dues, who may temporarily remove their residence for at least two years to a place more than fifty miles from Boston.

If any person elected a Foreign Honorary Member shall neglect for six months after being notified of his election to accept in writing, his election shall be void.

See Chap. vii, art. 2.

ARTICLE 5. Every Fellow resident within fifty miles of Boston hereafter elected shall pay an Admission Fee of Ten dollars, unless previously as an Associate he has paid an Admission Fee of like amount.

Every Fellow resident within fifty miles of Boston shall, and others may, pay such Annual Dues, not exceeding Fifteen dollars, as shall be voted by the Academy at each Annual Meeting, when they shall become due; but any Fellow shall be exempt from the annual payment if, at any time after his admission, he shall pay into the treasury Two hundred dollars in addition to his previous payments. Any Fellow shall also be exempt from Annual Dues who has paid such dues for forty years, or, having attained the age of seventy-five has paid dues for twenty-five years.

Fellows residing more than fifty miles from Boston elected after 1938 shall, and other non-resident Fellows may, pay annual dues of five dollars, which shall entitle them to all privileges of resident Fellows.

All Commutations of the Annual Dues shall be and remain permanently funded, the interest only to be used for current expenses.

Any Fellow not previously subject to Annual Dues who takes up his residence within fifty miles of Boston, shall pay to the treasurer within three months thereafter Annual Dues for the current year, failing which his Fellowship shall cease; but the Council may suspend the provisions of this Article for a reasonable time.

Only Fellows who pay Annual Dues or have commuted them may hold office in the Academy or serve on the Standing Committees or vote at meetings.

ARTICLE 6. Fellows who pay or have commuted the Annual Dues and Foreign Honorary Members shall be entitled to receive gratis one copy of all numbers of the Proceedings and Memoirs of the Academy which have been issued after their election.

See Chap. xi, art. 2.

ARTICLE 7. Diplomas signed by the President and the Vice-President of the Class to which the member belongs, and countersigned by the Secretaries, shall be given to Foreign Honorary Members and to Fellows.

ARTICLE 8. If, in the opinion of a majority of the entire Council, any Fellow or Foreign

Honorary Member shall have rendered himself unworthy of a place in the Academy, the Council shall recommend to the Academy the termination of his membership; and if three-fourths of the Fellows present, out of a total attendance of not less than fifty at a Stated Meeting, or at a Special Meeting called for the purpose, shall adopt this recommendation, his name shall be stricken from the Roll.

See Chap. iii; chap. vi, art. 1; chap. x, art. 1; chap. xi, art. 2.

CHAPTER III.

ELECTION OF FELLOWS AND FOREIGN HONORARY MEMBERS.

The procedure in the election of Fellows and Foreign Honorary Members shall be as follows:

Nominations to Fellowship or Foreign Honorary Membership in any Section must be signed by two Fellows of that Section, or by three Fellows of any Section, and sent to the Corresponding Secretary accompanied by a statement of the qualifications of the nominee and brief biographical data.

Notice shall be sent to every Fellow not later than the fifteenth of January in each year, reminding him that all nominations must be in the hands of the Corresponding Secretary before the first of February following.

The Corresponding Secretary shall, on the second of February, transmit to the several Vice-Presidents the nominations for Fellows and Foreign Honorary Members in their respective classes. Each Class Committee shall, before the sixteenth of February, consider the nominations, and may add others for the purpose of securing proper membership in the Academy, to the end that those in the country of highest distinction in their several classes may be Fellows.

A list of the nominees, giving a brief account of each, with the names of the nominators, shall be sent to every Fellow with a request that he return the list with such confidential comments and indications of preference as he may choose to make.

All the nominations, with any comments thereon and with expressions of preference on the part of the Fellows, shall be referred to the appropriate Class Committees, which shall canvass them, and report their recommendations in writing to the Council before the Stated Meeting of the Academy in April.

Elections of Fellows and Foreign Honorary Members shall be made by the Council before the Annual Meeting in May, and announced at that meeting.

Persons nominated in any year, but not elected, may be carried over to the list of nominees for the next year at the discretion of the Council, but shall not be further continued unless renominated.

See Chap. ii; chap. vi, art. 1; chap. x, art. 1.

CHAPTER IV.

OFFICERS.

ARTICLE 1. The Officers of the Academy shall be a President (who shall be Chairman of the Council), four Vice-Presidents (one from each Class), a Corresponding Secretary (who shall be Secretary of the Council), a Recording Secretary, a Treasurer, a Librarian, and an Editor, all of whom shall be elected by ballot at the Annual Meeting, and shall hold their respective offices for one year, and until others are duly chosen and installed.

There shall be also sixteen Councillors, one from each Section of each Class. At each Annual Meeting four Councillors, one from each Class, shall be elected by ballot to serve for the full term of four years and until others are duly chosen and installed. The same Fellows shall not be eligible for two successive terms.

The Councillors, with the officers previously named, and the Chairmen of the House Committee and the Committee on Resources and Policy, *ex officiis*, shall constitute the Council.

See Chap. xi, art. 1.

ARTICLE 2. If any officer be unable, through death, absence, or disability, to fulfill the duties of his office, or if he shall resign, his place may be filled by the Council in its discretion for any part or the whole of the unexpired term.

ARTICLE 3. At the Stated Meeting in March, the President shall appoint a Nominating Committee of four Fellows having the right to vote, one from each Class. This Committee shall prepare a list of nominees for the several offices to be filled, and for the Standing Committees, and file it with the Recording Secretary not later than four weeks before the Annual Meeting.

See Chap. vi, art. 2.

ARTICLE 4. Independent nominations for any office, if signed by at least twenty Fellows having the right to vote, and received by the Recording Secretary not less than ten days before the Annual Meeting, shall be inserted in the call therefor, and shall be mailed to all the Fellows having the right to vote.

See Chap. vi, art. 2.

ARTICLE 5. The Recording Secretary shall prepare for use in voting at the Annual Meeting a ballot containing the names of all persons duly nominated for office.

CHAPTER V.

THE PRESIDENT.

ARTICLE 1. The President, or in his absence the senior Vice-President present (seniority to be determined by length of continuous Fellowship in the Academy), shall preside at all meetings of the Academy. In the absence of all these officers, a Chairman of the meeting shall be chosen by ballot.

ARTICLE 2. Unless otherwise ordered, all Committees which are not elected by ballot shall be appointed by the presiding officer.

ARTICLE 3. Any deed or writing to which the Corporate Seal is to be affixed, except leases of real estate, shall be executed in the name of the Academy by the President or, in the event of his death, absence, or inability, by one of the Vice-Presidents, when thereto duly authorized.

See Chap. ii, art. 7; chap. iv, art. 1, 3; chap. vi, art. 2; chap. vii, art. 1; chap. x, art. 6; chap. xi, art. 1, 2; chap. xii, art. 1.

CHAPTER VI.

THE SECRETARIES.

ARTICLE 1. The Corresponding Secretary shall conduct the correspondence of the Academy and of the Council, recording or making an entry of all letters written in its name, and preserving for the files all official papers which may be received. At each meeting of the Council he shall present the communications addressed to the Academy which have been received since the previous meeting, and at the next meeting of the Academy he shall present such as the Council may determine.

He shall notify all persons who may be elected Fellows or Foreign Honorary Members, send to each a copy of the Statutes, and on their acceptance issue the proper Diploma. He shall also notify all meetings of the Council; and in case of the death, absence, or inability of the Recording Secretary he shall notify all meetings of the Academy.

Under the direction of the Council, he shall keep a List of the Fellows and Foreign Honorary Members, arranged in their several Classes and Sections. It shall be printed annually and issued as of the first day of July.

See Chap. ii, art. 7; chap. iii; chap. iv, art. 1; chap. x, art. 6; chap. xi, art. 1; chap. xii, art. 1.

ARTICLE 2. The Recording Secretary shall have the custody of the Charter, Corporate Seal, Archives, Statute-Book, Journals, and all literary papers belonging to the Academy.

Fellows borrowing such papers or documents shall receipt for them to their custodian.

The Recording Secretary shall attend the meetings of the Academy and keep a faithful record of the proceedings with the names of the Fellows present; and after each meeting is duly opened, he shall read the record of the preceding meeting.

He shall notify the meetings of the Academy to each Fellow and by mail at least seven days beforehand, and in his discretion may also cause the meetings to be advertised; he shall apprise Officers and Committees of their election or appointment, and inform the Treasurer of appropriations of money voted by the Academy.

After all elections, he shall insert in the Records the names of the Fellows by whom the successful nominees were proposed.

He shall send the Report of the Nominating Committee in print to every Fellow having the right to vote at least three weeks before the Annual Meeting.

See Chap. iv, art. 3.

In the absence of the President and of the Vice-President he shall, if present, call the meeting to order, and preside until a Chairman is chosen.

See Chap. i; chap. ii, art. 7; chap. iv, art. 3, 4, 5; chap. x, art. 6; chap. xi, art. 1, 2; chap. xii, art. 1, 3.

ARTICLE 3. The Secretaries, with the Editor, shall have authority to publish such of the records of the meetings of the Academy as may seem to them likely to promote its interests.

CHAPTER VII.

THE TREASURER AND THE TREASURY.

ARTICLE 1. The Treasurer shall collect all money due or payable to the Academy and all gifts or bequests made to it. He shall pay all bills due and payable by the Academy when approved by the proper officers. He shall sign all leases of real estate in the name of the Academy. He shall be the official custodian of all bonds, stocks and other securities and, with the written approval of any one member of the Committee on Finance, he shall have full authority to sell and transfer, invest and reinvest from time to time in such manner and upon such terms as shall to him seem best, the whole or any part of the personal property of the said Academy.

He shall keep a faithful account of all receipts and expenditures, submit his accounts annually to the Auditing Committee, and render them at the expiration of his term of office, or whenever required to do so by the Academy or the Council.

He shall keep separate accounts of the income of the Rumford Fund, and of all other special Funds, and of the Appropriation thereof, and render them annually.

His accounts shall always be open to the inspection of the Council.

ARTICLE 2. He shall report annually to the Council at its March meeting on the expected income of the various Funds and from all other sources during the ensuing financial year. He shall also report the names of all Fellows who may be then delinquent in the payment of their Annual Dues.

ARTICLE 3. He shall give such security for the trust reposed in him as the Academy may require.

ARTICLE 4. With the approval of a majority of the Committee on Finance, he may appoint an Assistant Treasurer to perform his duties, for whose acts, as such assistant, he shall be responsible; or, with like approval and responsibility, he may employ any Trust Company doing business in Boston as his agent for the same purpose, the compensation of such Assistant Treasurer or agent to be fixed by the Committee on Finance and paid from the Funds of the Academy.

ARTICLE 5. At the Annual Meeting he shall report in print all his official doings for the preceding year, stating the amount and condition of all the property of the Academy entrusted to him, and the character of the investments.

ARTICLE 6. The Financial Year of the Academy shall begin with the first day of April.

ARTICLE 7. No person or committee shall incur any debt or liability in the name of the Academy, unless in accordance with a previous vote and appropriation therefor by the Academy or the Council, or sell or otherwise dispose of any property of the Academy, except cash or invested funds, without previous consent and approval of the Council.

See Chap. ii, art. 4, 5; chap. vi, art. 2; chap. x, art. 6; chap. xi, art. 1, 2, 3; chap. xii, art. 1.

CHAPTER VIII.

THE LIBRARIAN AND THE LIBRARY.

ARTICLE 1. The Librarian shall have charge of the printed books, keep a correct catalogue thereof, and provide for their delivery from the Library.

At the Annual Meeting, as Chairman of the Committee on the Library, he shall make a Report on its condition.

Article 2. In conjunction with the Committee on the Library he shall have authority to expend such sums as may be appropriated by the Academy for the purchase of books, periodicals, etc., and for defraying other necessary expenses connected with the Library.

Article 3. All books procured from the income of the Rumford Fund or of other special Funds shall contain a book-plate expressing the fact.

Article 4. Books taken from the Library shall be receipted for to the Librarian or his assistant.

Article 5. Books shall be returned in good order, regard being had to necessary wear with good usage. If any book shall be lost or injured, the Fellow to whom it stands charged shall replace it by a new volume or by a new set, if it belongs to a set, or pay the current price thereof to the Librarian, whereupon the remainder of the set, if any, shall be delivered to the Fellow so paying, unless such remainder be valuable by reason of association.

Article 6. All books shall be returned to the Library for examination at least one week before the Annual Meeting.

Article 7. The Librarian shall have the custody of the Publications of the Academy. With the advice and consent of the President, he may effect exchanges with other associations.

See Chap. ii, art. 6; chap. xi, art. 1, 2.

CHAPTER IX.

The Editor and the Publications.

Article 1. The Editor shall have charge of the conduct through the press of the Proceedings and the Memoirs, and all correspondence relative thereto, and shall have power to fix the price at which individual numbers of the Proceedings and Memoirs are sold.

The Editor shall select as Associate Editor one member of the Committee of Publication, and the Associate Editor shall assist the Editor in the duties of his office in such way as the two shall find most convenient.

Article 2. In conjunction with the Committee of Publication, the Editor shall have authority to expend such sums as may be appropriated by the Academy for printing the publications and for defraying other expenses therewith connected.

Article 3. All publications which are financed in whole or in part from the income of the Rumford Fund or from the income of other special funds, and all publications of work done with the aid of the Rumford Fund or other special funds, shall contain a conspicuous statement of this fact.

Article 4. Two hundred extra copies of each paper printed in the Proceedings or Memoirs shall be placed at the disposal of the author without charge.

If, on account of the number of communications offered for publication, it shall be necessary to decline for publication communications otherwise acceptable, members of the Academy shall be given preference in each of the several Classes over non-members; but whenever it shall be necessary to exercise this preference, the Editor shall inform the Council of the fact.

See Chap. iv, art. 1; chap. vi, art. 3; chap. x, art. 6; chap. xi, art. 2, sect. 5.

CHAPTER X.

The Council.

Article 1. The Council shall exercise a discreet supervision over all nominations and elections to membership, and in general supervise all the affairs of the Academy not explicitly reserved to the Academy as a whole or entrusted by it or by the Statutes to standing or special committees.

It shall consider all nominations duly sent to it by any Class Committee, and act upon them in accordance with the provisions of Chapter III.

With the consent of the Fellow interested, it shall have power to make transfers between the several Sections, reporting its action to the Academy.

See Chap. iii; chap. xi, art. 1.

ARTICLE 2. Nine members shall constitute a quorum.

ARTICLE 3. It shall establish rules and regulations for the transaction of its business, and provide all printed and engraved blanks and books of record.

ARTICLE 4. It shall act upon all resignations of officers, and all resignations and forfeitures of Fellowship; and cause the Statutes to be faithfully executed.

It shall appoint all agents and subordinates not otherwise provided for by the Statutes, prescribe their duties, and fix their compensation. They shall hold their respective positions during the pleasure of the Council.

ARTICLE 5. It may appoint, for terms not exceeding one year, and prescribe the functions of, such committees of its number, or of the Fellows of the Academy, as it may deem expedient, to facilitate the administration of the affairs of the Academy or to promote its interests.

ARTICLE 6. At its March meeting it shall receive reports from the President, the Secretaries, the Treasurer, and the Standing Committees, on the appropriations severally needed for the ensuing financial year. At the same meeting the Treasurer shall report on the expected income of the various Funds and from all other sources during the same year.

A report from the Council shall be submitted to the Academy, for action, at the March meeting, recommending the appropriation which in the opinion of the Council should be made.

On the recommendation of the Council, special appropriations may be made at any Stated Meeting of the Academy, or at a Special Meeting called for the purpose.

See Chap. xi, art. 3.

ARTICLE 7. It shall report at every meeting of the Academy such business as it may deem advisable to present.

See Chap. ii, art. 4, 5, 8; chap. iv, art. 1, 2; chap. vi, art. 1; chap. vii, art. 1; chap. xii, art. 1, 4.

CHAPTER XI.

STANDING COMMITTEES.

ARTICLE 1. The Class Committee of each Class shall consist of the Vice-President, who shall be chairman, and the four Councillors of the Class, together with such other officer or officers annually elected as may belong to the Class. It shall consider nominations to Fellowship in its own Class, and report in writing to the Council such as may receive at a Class Committee Meeting a majority of the votes cast, provided at least three shall have been in the affirmative.

See Chap. iii.

ARTICLE 2. At the Annual Meeting the following Standing Committees shall be elected by ballot to serve for the ensuing year.

(i) *The Committee on Finance,* to consist of four Fellows, who shall have general oversight of the funds and investments of the Academy.

See Chap. iv, art. 3; chap. vii, art. 1, 4; chap. x, art. 6.

(ii) *The Committee on Policy and Resources* to consist of five Fellows and the President, *ex officio,* one of the five elected members to be elected each year to serve for a term of five years, except that the five elected in 1939 shall be elected for terms of one, two, three, four, and five years respectively, the Committee to concern itself with procuring funds for the Academy, to study the activities and needs of the Academy, and to recommend, for the approval of the Council, means by which the functions and purposes of the Academy may best be fulfilled.

(iii) *The Rumford Committee,* to consist of seven Fellows, who shall report to the Academy on all applications and claims for the Rumford Premium. It alone shall authorize the purchase of books, publications and apparatus at the charge of the income from the Rumford Fund, and generally shall see to the proper execution of the trust.

See Chap. iv, art. 3; chap. x, art. 6.

(iv) *The Cyrus Moors Warren Committee,* to consist of seven Fellows, who shall consider all applications for appropriations from the income of the Cyrus Moors Warren Fund, and generally shall see to the proper execution of the trust.

See Chap. iv, art. 3; chap. x, art. 6.

(v) *The Committee of Publication,* to consist of the Editor, *ex officio,* as Chairman, and four other Fellows, one from each Class, to whom all communications submitted to the Academy for publication shall be referred, and to whom the printing of the Proceedings and the Memoirs shall be entrusted.

It shall fix the price at which volumes of the publications shall be sold, but Fellows may be supplied at half price with volumes and with single publications which they are not entitled to receive gratis.

It shall determine when the pressure of material offered for publication makes it necessary to give preference to members of the Academy as compared with non-members, or to give priority to certain members as compared with others, and to what extent this preference or priority shall be applied in each of the four Classes, to the end that a proper balance of the facilities of publication with respect to subject matter and authors may be maintained.

See Chap. iv, art. 3; chap. vi, art. 1, 3; chap. ix; chap. x, art. 6.

(vi) *The Committee on the Library,* to consist of the Librarian, *ex officio,* as Chairman, and four other Fellows, one from each Class, who shall examine the Library and make an annual report on its condition and management.

See Chap. iv, art. 3; chap. viii, art. 1, 2; chap. x, art. 6.

(vii) *The House Committee,* to consist of four Fellows, who shall have charge of all expenses connected with the House, including the general expenses of the Academy not specifically assigned to the care of other Committees or Officers.

See Chap. iv, art. 1, 3; chap. x, art. 6.

(viii) *The Committee on Meetings,* to consist of the President, the Recording Secretary, and four other Fellows, who shall have charge of plans for meetings of the Academy.

See Chap. iv, art. 3; chap. x, art. 6.

(ix) *The Auditing Committee,* to consist of two Fellows, who shall audit the accounts of the Treasurer, with power to employ an expert and to approve his bill.

See Chap. iv, art. 3; chap. vii, art. 1; chap. x, art. 6.

(x) *The Committee on Biographical Notices,* to consist of six Fellows, two to be elected each year, one of them to be a Secretary of the Academy, to see that biographical records of the Fellows and Foreign Honorary Members are provided.

ARTICLE 3. The Standing Committees shall report annually to the Council in March on the appropriations severally needed for the ensuing financial year; and all bills incurred on account of these Committees, within the limits of the several appropriations made by the Academy, shall be approved by their respective Chairmen.

In the absence of the Chairman of any Committee, bills may be approved by any member of the Committee whom he shall designate for the purpose.

See Chap. vii, art. 1, 7; chap. x, art. 6.

CHAPTER XII.

MEETINGS, COMMUNICATIONS, AND AMENDMENTS.

ARTICLE 1. There shall be annually eight Stated Meetings of the Academy, namely, on the second Wednesday of October, November, December, January, February, March, April, and May. Only at these meetings, or at adjournments thereof regularly notified, or at Special Meetings called for the purpose, shall appropriations of money be made or amendments of the Statutes or Standing Votes be effected.

The Stated Meeting in May shall be the Annual Meeting of the Corporation.

Special Meetings shall be called by either of the Secretaries at the request of the President, of a Vice-President, of the Council, or of ten Fellows having the right to vote; and notifications thereof shall state the purpose for which the meeting is called.

The Council shall have authority, as occasion may demand, to arrange additional meetings and to cancel any of the Statutory meetings, except that meetings for transacting business shall be held as required by the Statutes.

ARTICLE 2. Twenty-five Fellows having the right to vote shall constitute a quorum for the transaction of business at Stated or Special Meetings. Eighteen Fellows shall be sufficient to constitute a meeting for literary or scientific communications and discussions.

ARTICLE 3. Upon the request of the presiding officer or the Recording Secretary, any motion or resolution offered at any meeting shall be submitted in writing.

ARTICLE 4. No report of any paper presented at a meeting of the Academy shall be published by any Fellow without the consent of the author; and no report shall in any case be published by any Fellow in a newspaper as an account of the proceedings of the Academy without the previous consent and approval of the Council. The Council, in its discretion, by a duly recorded vote, may delegate its authority in this regard to one or more of its members.

ARTICLE 5. Fellows may introduce guests at any of the literary or scientific meetings of the Academy.

ARTICLE 6. The Academy shall not express its judgment on literary or scientific memoirs or performances submitted to it, or included in its Publications.

ARTICLE 7. All proposed Amendments of the Statutes shall be referred to a committee, and on its report, at a subsequent Stated Meeting or at a Special Meeting called for the purpose, two-thirds of the ballots cast, and not less than twenty-five, must be affirmative to effect enactment.

ARTICLE 8. Standing Votes may be passed, amended, or rescinded at a Stated Meeting, or at a Special Meeting called for the purpose, by a vote of two-thirds of the members present. They may be suspended by a unanimous vote.

See Chap. ii, art. 5, 8; chap. iii; chap. iv, art. 3, 4, 5; chap. v. art. 1; chap. vi, art. 1, 2; chap. x, art. 7.

STANDING VOTES

1. Communications of which notice has been given to either of the Secretaries shall take precedence of those not so notified.

2. Fellows may take from the Library six volumes at any one time, and may retain them for three months, and no longer. Upon special application, and for adequate reasons assigned, the Librarian may permit a larger number of volumes, not exceeding twelve, to be drawn from the Library for a limited period.

3. Works published in numbers, when unbound, shall not be taken from the Hall of the Academy without the leave of the Librarian.

4. Communications offered for publication in the Proceedings or Memoirs of the Academy shall not be accepted for publication before the author either himself or through some agent, shall have informed the Committee on Meetings of his readiness to use such time as the Committee may assign him at such meeting as may be convenient both to him and to the Committee, for the purpose of presenting to the Academy a general statement of the nature and significance of the results contained in his communication.

RUMFORD PREMIUM

In conformity with the terms of the gift of Sir Benjamin Thompson, Count Rumford, of a certain Fund to the American Academy of Arts and Sciences, and with a decree of the Supreme Judicial Court of Massachusetts for carrying into effect the general charitable intent and purpose of Count Rumford, as expressed in his letter of gift, the Academy is empowered to make from the income of the Rumford Fund, as it now exists, at any Annual Meeting, an award of a gold and a silver medal, being together of the intrinsic value of three hundred dollars, as a Premium to the author of any important discovery or useful improvement in light or heat, which shall have been made and published by printing, or in any way made known to the public, in any part of the continent of America, or any of the American islands; preference always being given to such discoveries as, in the opinion of the Academy, shall tend most to promote the good of mankind; and, if the Academy sees fit, to add to such medals, as a further Premium for such discovery and improvement, a sum of money not exceeding three hundred dollars.

PERMANENT SCIENCE FUND

By an Agreement and Declaration of Trust dated Sept. 5, 1928, the Boston Safe Deposit and Trust Company agrees to accept and hold gifts made to it as Trustee of the Permanent Science Fund . . . and to pay the income . . . to the American Academy of Arts and Sciences, to be applied to such scientific research "as shall be deemed charitable within the broadest possible construction of that term" . . . in such sciences as Mathematics, Physics, Chemistry, Astronomy, Geology, Geography, Zoology, Botany, Anthropology, Psychology, Sociology and Economy, History and Philology, Engineering, Medicine and Surgery, Agriculture, Manufacture and Commerce, Education and any other science of any nature or description whether or not now known or now recognized as scientific; and may be applied to or through public or private associations, societies or institutions, . . . or to or through one or more individuals.

Disbursements from income are voted by the Council of the Academy upon recommendations from the Committee on the Permanent Science Fund. A brochure comprising the First Decennial Report on the history and activities of this committee and a copy of the Agreement and Declaration of Trust is available on request to the Trustee at 100 Franklin Street, Boston, Mass.

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